SAND2017-10310R

EPRI/DOE High-Burnup Fuel Sister Rod Test Plan Simplification and Visualization

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel & Waste Science & Technology

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September 15, 2017

SFWD-SFWST-20XX-XXXX
National Laboratory Report No. XXXXXX

SUMMARY

The EPRI/DOE High-Burnup Confirmatory Data Project (herein called the “Demo”) is a multi-year, multi-entity test with the purpose of providing quantitative and qualitative data to show if high-burnup fuel mechanical properties change in dry storage over a ten-year period. The Demo involves obtaining 32 assemblies of high-burnup PWR fuel of common cladding alloys from the North Anna Nuclear Power Plant, loading them in an NRC-licensed TN-32B cask, drying them according to standard plant procedures, and then storing them on the North Anna dry storage pad for ten years. After the ten-year storage time, the cask will be opened and the mechanical properties of the rods will be tested and analyzed.

Twenty-five rods from assemblies of similar claddings, in-reactor placement, and burnup histories (herein called “sister rods”) have been shipped from the North Anna Nuclear Power Plant and are currently being nondestructively tested at Oak Ridge National Laboratory. After the non-destructive testing has been completed for each of the twenty-five rods, destructive analysis will be performed to obtain mechanical data. The purpose of this testing is to provide baseline mechanical property data that will be used as a comparison to the mechanical data collected from the Demo rods after ten years of storage.

Oak Ridge National Laboratory and Pacific Northwest National Laboratory both wrote detailed test plans for the sister rods which are in the appendices of this document. This document is a simplification and visualization of a preliminary set of tests to be performed on the sister rods which draws from the ORNL and PNNL plans. The purpose of the graphic is to communicate the overall initial plan to a wider audience. After this testing is complete, the team will reconvene to determine additional testing.

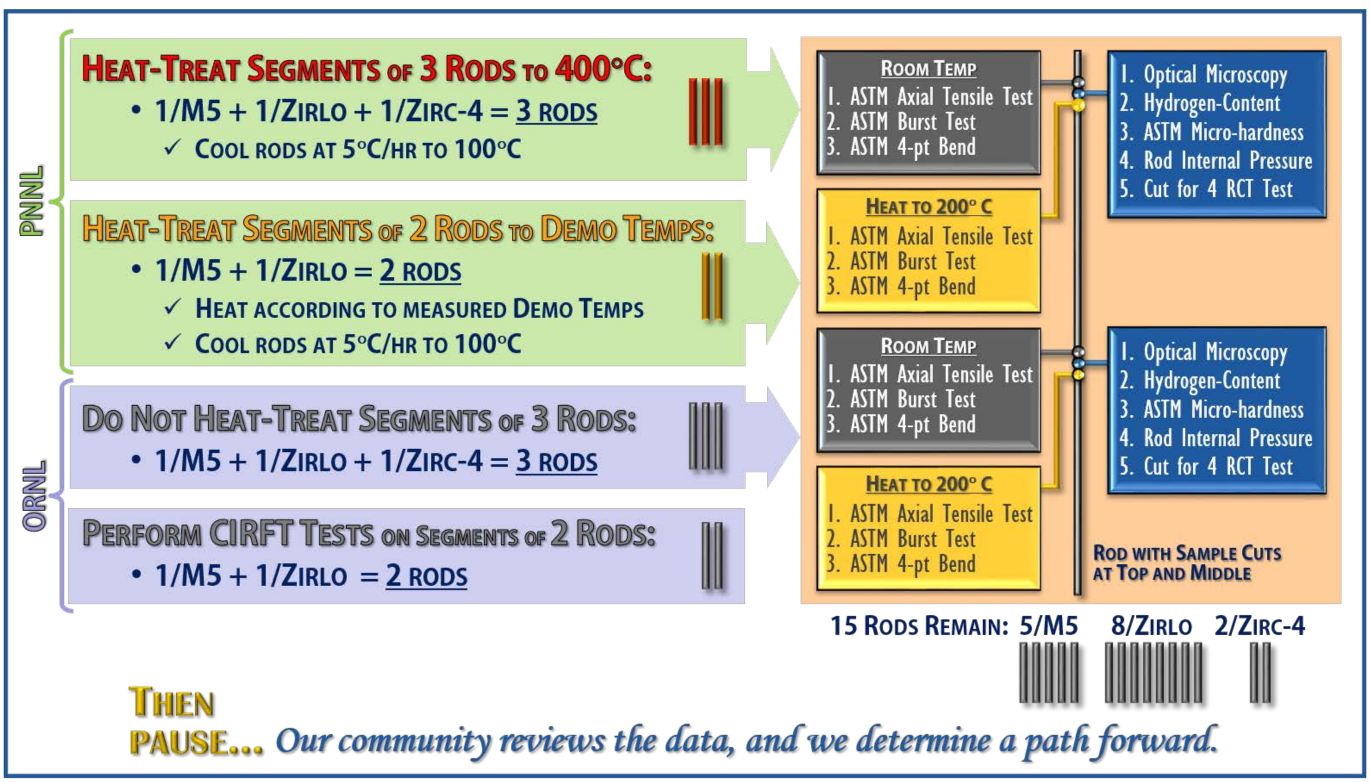

Figure 1. Test Plan Visualization

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ACKNOWLEDGEMENTS

Much thanks is given to Ned Larson who has been a constant source of excellent management and leadership and who has provided encouragement, ideas, structure, problem-solving and funding.

Thanks go to Mike Billone from Argonne National Laboratory and Albert Machiels from EPRI who spent many hours helping simplify the multitude of ideas into this plan. In addition, Ricardo Torres from the NRC provided great opinions, insight, and the regulatory perspective that was very important in focusing the scope of the testing. Additional thanks are given to the rest of the expert team, Keith Waldrop and Aladar Csontos from EPRI, Kris Cummings from NEI, Ken Sorenson from Sandia National Labs, John Kessler from Kessler Associates, Halim Alsaed from Environuclear, and Ned Larson from DOE.

Most importantly, thanks goes to the teams at ORNL and PNNL for the time thinking about, designing, and discussing the best tests.

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REVISION HISTORY

ACRONYMS

ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
CIRFT	Cyclic Integrated Reversible-Bending Fatigue Tester
DOE	US Department of Energy
DOE NE	US Department of Energy - Office of Nuclear Energy
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
IFBA	Integrated Fuel Burnable Absorber
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
SNL	Sandia National Laboratories

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STORAGE AND TRANSPORTATION TECHNOLOGIES

1. BACKGROUND

The EPRI/DOE High-Burnup Confirmatory Data Project (herein called the "Demo") is a multi-year, multi-entity confirmation demonstration test with the purpose of providing quantitative and qualitative data to show how high-burnup fuel ages in dry storage over a ten-year period. The Demo involves storing 32 assemblies of high-burnup PWR fuel of four different cladding alloys from the North Anna Nuclear Power Plant, loading them in an NRC-licensed TN-32B cask, drying them per standard plant procedures, and then storing on the North Anna dry storage pad for ten years. After the ten-year storage time, the cask will be opened and the mechanical properties of the rods will be examined.

Ideally, rods of similar histories would be tested before the ten-year storage time to provide baseline data for comparison to the 10-year stored rods. To do this, twenty-five rods (herein called "sister rods") from assemblies of similar claddings, in-reactor placement, and burnup histories have been shipped from the North Anna Nuclear Power Plant and are currently being nondestructively tested at Oak Ridge National Laboratory (ORNL). After the non-destructive testing has been completed for each of the twenty-five rods, approximately one-half of one rod equivalent will be shipped to Argonne National Laboratory (ANL), ten rod equivalents will be shipped to Pacific Northwest National Laboratory (PNNL), and the remaining rods will stay at ORNL for destructive testing. PNNL and ORNL have written test plans for those rods. The ANL testing plan is described within the ORNL plan, and those plans are attached to this plan in the appendices and therefore detailed technical information will not be repeated in this document because it is covered in the attached plans.

After numerous reviews and discussions about the ANL, PNNL, and ORNL plans, concerns were voiced by different parties. A summary of those concerns is below.

- The test plans are ***too complicated*** to explain to people and a simple visual is needed to communicate the plan.
- The plans contain ***too many tests***.
    - Numerous tests were designed to collect data on the same mechanical property which may produce slightly different results and may be difficult to reconcile in the future.
    - Many of the proposed tests did not have a testing pedigree (such as ASTM) and therefore may be harder to duplicate ten-years from now.
    - Tests proposed allowed for too many variables.
- This ***effort has been turned into a "science project***" instead of efficiently and effectively obtaining a few data points on a few key properties that can be compared to mechanical property data collected on the stored rods ten years from now.
- The use of the words "filling the gaps" bothered some who remind the team that this is a ***confirmatory test project, not a gap-filling project***.
- This testing campaign is far more than just an opportunity to obtain confirmatory data. ***This is an excellent opportunity to collect data on high-burnup fuel*** and it should not be missed. After the high-priority testing, if there is budget, more data can be obtained from the 25 high-burnup sister rods.

These discussions narrow the focus of the sister rod test plans' purpose and goals:

Purpose: To provide baseline mechanical property data that will be used as a comparison to the mechanical data collected from the Demo rods after ten years of storage.

Goals:

1. ***Identify types and number of tests*** to provide a core set of material property and physical data that can be compared to the ten-year stored rods. Develop a simple visual that describes the test plan.
2. ***Provide core baseline data*** of the pre-stored rods for comparison to post stored-rods.
3. ***Maximize the effect of hydride reorientation into the radial orientation during drying to heat treating to 400°C.***

The concerns and goals summarized above initiated DOE NE's request that a simplified test plan with a descriptive visual be developed. This document provides that simplified plan.

2. THE SIMPLIFIED TEST PLAN

Based on the ORNL and PNNL test plans and the discussions and expert opinions summarized in this document, the consolidated and simplified test plan is described below. Consideration was given to what core data is important and what test methods would obtain that data using respected and reproducible methods. The plan is heavily based on the input from the interviewed experts and feedback during the EPRI ESCP and NEI Used Fuel Management conferences in Savannah, Georgia, May 1-4, 2017.

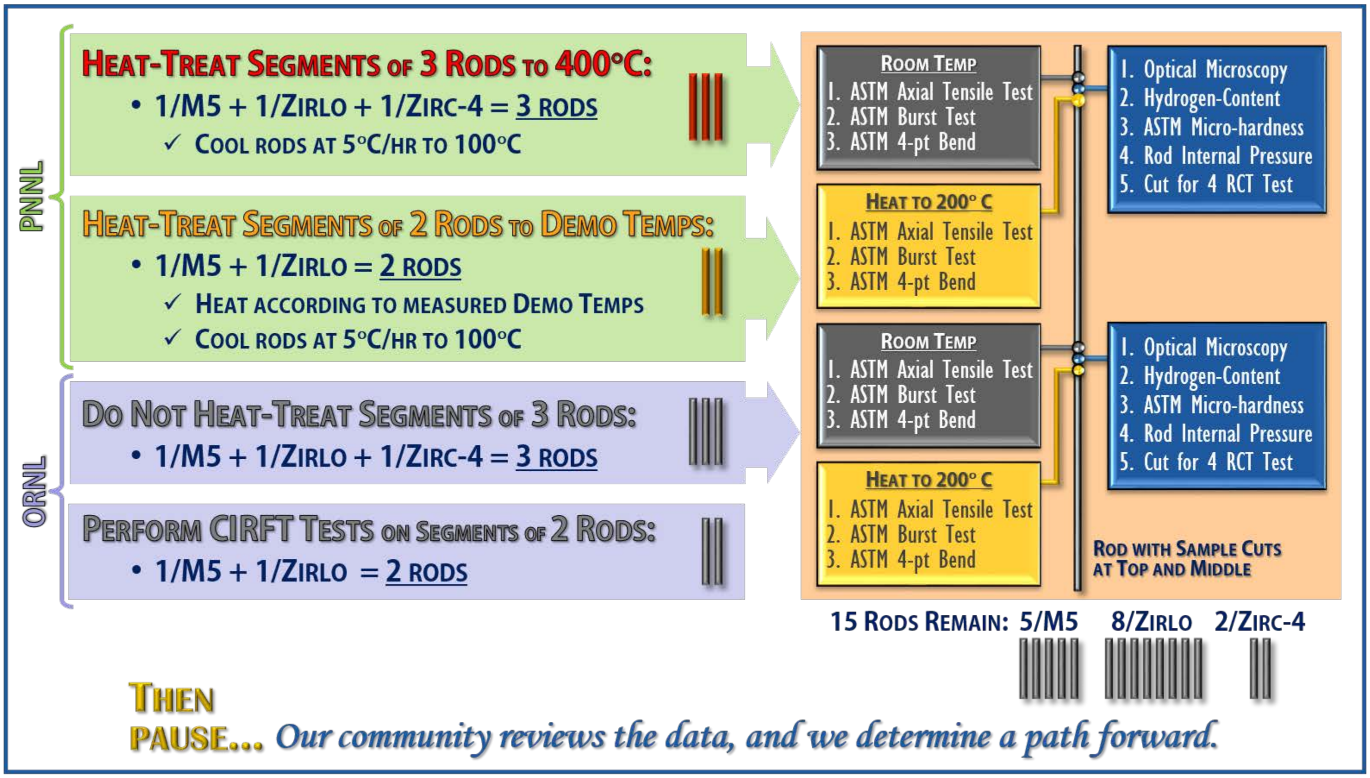

Figure 1. Test Plan Visualization

The process steps for conducting the simplified test plan are as follows.

1. ORNL will measure the rod internal pressure and microhardness for each of the 25 rods, addressing the ten rods destined for PNNL first. The ten, punctured, full-length rods will be shipped from ORNL to PNNL in FY18.
2. ORNL & PNNL: Gas communication will be measured in both the PNNL and ORNL rods at their respective facilities.
3. PNNL: One of each rod cladding type (1 M5, 1 Zirlo, and 1 Zirc-4) will be cut, sealed and pressurized to End-of-Life Rod-Internal-Pressures representative of pressures at 400°C. Each rod segment will be heated to 400°C. A temperature profile will not be used when heating the rods in order to reduce variability between samples and to maximize the effect of hydride reorientation into the radial orientation.

- **Cooling**: The rod segments will then be cooled at a rate of 5°C per hour until they reach 100°C at which time they can be cooled faster. [a]
- **Sample Cutting**: Samples will be cut from the top and the middle of the rod for the tests depicted in Figure 1. The bottom of the rod will be saved for future testing. Samples will be cut at the top of the rod for Axial Tensile, Burst, 4-pt Bend, optical microscopy, hydrogen content, micro hardness,4 ANL Method Ring Compression Tests, ORNL Fueled Ring Compression Tests, Axial Tensile, Burst, and 4-pt bend test. The same pattern of cuts will be repeated at the middle section of the rod. Samples will then be prepared as required for each specific test and tested at PNNL. Note that some samples will need to be defueled and some will not.
- **Testing Temperatures**: The Axial Tensile, Burst, and 4-pt Bend Test will be tested at two different temperatures. The samples cut from the top portion of the upper and middle sections of the rod will be tested at room temperature. The samples cut from the bottom portion of the upper and middle sections of the rod will be reheated to 200°C and then tested at 200°C. The tests depicted in the blue box on the right in Figure 1 will be tested at room temperature.

4. PNNL: One M5 and one Zirlo rod will be will be cut, sealed, and pressurized to End-of-Life Rod-Internal-Pressures representative of pressures at the measured Demo temperatures. The rod segments will be heated according to the average peak demo temperatures recorded at rod elevation closest to the tested segment. The bottom of the rod will be saved for future testing.
   - **Cooling**: The rod segments will then be cooled at a rate of 5°C per hour until they reach 100°C at which time they can be cooled faster (see footnote a).
   - **Sample Cutting:** Samples will be cut from the top and the middle of the rod for the tests depicted in Figure 1. The bottom of the rod will be saved for future testing. Samples will be cut at the top of the rod for Axial Tensile, Burst, 4-pt Bend, optical microscopy, hydrogen content, micro hardness, 4 ANL Method Ring Compression Tests, ORNL Fueled Ring Compression Tests, Axial Tensile, Burst, and 4-pt bend test. The same pattern of cuts will be repeated at the middle section of the rod. Samples will then be prepared as required for each specific test and tested at PNNL. Note that some samples will need to be defueled and some will not.
   - **Testing Temperatures**: The Axial Tensile, Burst, and 4-pt Bend Test will be tested at two different temperatures. The samples cut from the top portion of the upper and middle sections of the rod will be tested at room temperature. The samples cut from the bottom portion of the upper and middle sections of the rod will be reheated to 200°C and then tested at 200°C. The tests depicted in the blue box on the right in Figure 1 will be tested at room temperature.
5. ORNL: One of each rod cladding type (1 M5, 1 Zirlo, and 1 Zirc-4) will be cut, sealed and pressurized to End-of-Life Rod-Internal-Pressures representative of the puncture test data.

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[a] PNNL and ANL are investigating cooling rates by testing unirradiated rods at different cooling rates between 1°C/hr and 5°C/hr and comparting micrographs of the cladding after cooling for differences in the resulting hydrides. Results from these tests will inform the final decision on the cooling rate.

- **Sample Cutting:** Samples will be cut from the top and the middle of the rod for the tests depicted in Figure 1. The bottom of the rod will be saved for future testing. Samples will be cut at the top of the rod for Axial Tensile, Burst, 4-pt Bend, optical microscopy, hydrogen content, micro hardness), 4 ANL Method Ring Compression Tests, ORNL Fueled Ring Compression Tests, Axial Tensile, Burst, and 4-pt bend test. The same pattern of cuts will be repeated at the middle section of the rod. Samples will then be prepared as required for each specific test and tested at ORNL. Note that some samples will need to be defueled and some will not.
- **Testing Temperatures**: The Axial Tensile, Burst, and 4-pt Bend Test will be tested at two different temperatures. The samples cut from the top portion of the upper and middle sections of the rod will be tested at room temperature. The samples cut from the bottom portion of the upper and middle sections of the rod will be reheated to 200°C and then tested at 200°C. The tests depicted in the blue box on the right in Figure 1 will be tested at room temperature.

6. ORNL: One M5 and one Zirlo rod will be cut into segments and pressurized and heated to 400°C (no temperature profile) and Demo Temperatures for performing numerous CIRFT tests along the length of the rod. The rod segments will not undergo temperature cycling. They will be re-pressurized to the Demo and 400°C rod internal pressure (per calculations) It may not be possible to perform the tests while heated at 200°C, but it is desired to compare the mechanical properties obtained in the CIRFT tests to the other mechanical properties obtained in this test plan.
7. ANL: ANL will perform Ring Compression Tests according to their current procedure. Test will be performed on eight defueled rings per rod, four at the top and four at the middle, to determine ductility.

After this testing is complete, the community will review the data and determine if further testing is needed. Additional attention will be given after this first round of testing to testing at grid spacers, different temperature and pressure conditions to capture the sample-to-sample variability and to capture more axial and circumferential variability in the rods, IFBA bounding rod-internal-pressures, and more fueled rod samples.

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APPENDIX I. POST-IRRADIATION EXAMINATION PLAN FOR HIGH BURNUP DEMONSTRATION PROJECT SISTER RODS

PREDECISIONAL DRAFT

Post-Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

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December 30, 2016
SFWD-SFWST-2017-000090
ORNL/SR-2016/708

SUMMARY

Twenty-five high burnup (HBU) (>45 GWd/MTU) fuel rods were extracted from seven different spent nuclear fuel (SNF) assemblies operated at the North Anna nuclear power plant and in 2016 were shipped to ORNL for detailed nondestructive examination (NDE) and destructive examination (DE). These HBU fuel rods are “sister rods” to SNF that will be placed in dry storage in a modified TN-32B cask, the research project cask (RPC). The connotation “sister rod” indicates that these fuel rods have similar characteristics to fuel rods in the RPC because they have been extracted from assemblies with the same design and similar operating histories (symmetric partners) or from the actual fuel assemblies that will be included in the RPC. The sister rods include four cladding types: Zirlo, M5, Zircaloy-4 (Zirc-4), and low-tin Zirc-4. The sister rods are representative of HBU post-operation and pre-dry storage conditions.

This test plan describes the experimental work to be performed by Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE) Office of Nuclear Energy on the sister rods and serves to coordinate ORNL’s multiyear experimental program. The data collected will be used in conjunction with the High Burnup Dry Storage Cask Research and Development Project [1]. The work began in fiscal year (FY) 2016 and is expected to continue through FY 2027. The work scope includes the specification of relevant testing, development (as necessary) of required test protocols and fixturing, performance of the tests, oversight of measurements, collection and interpretation of relevant data, and summary reports.

The detailed examinations specified within this plan will provide performance characteristics, material property data, and mechanical performance properties on the sister rods to establish

- the baseline condition of the HBU SNF rods in the post-operation and pre-dry storage condition, including the cladding, the fuel pellets and the integrated cladding/pellet system;
- changes in HBU rods, cladding, and pellets resulting from dry storage activities (as observed at room temperature);
- data from HBU SNF exposed to temperatures higher than those that will be achieved in the RPC to expand the applicability of the dry storage project, and
- general SNF characteristics data for HBU fuels, including mechanical properties that can be used to expand the applicability of the sister rod data across the industry fleet of casks and to support code validation and future analysis needs prior to the RPC being opened.

Similar examinations may be performed on HBU SNF rods extracted from the RPC (the “cask rods”) at the end of the dry storage period, which may be up to 10 years or longer, to identify any changes that may have occurred during dry storage. The ultimate goal of the work described in this test plan is to provide the data needed to address the technical gaps associated with long-term storage and transportation of HBU SNF [2,3,4]. The DEs are specified to provide sufficient data to allow more precise analytical predictions of pressurized water reactor (PWR) SNF performance during all conditions of transport and storage. Although there are similarities between PWR and boiling water reactor (BWR) fuel, these examinations are partially applicable to BWR SNF.

Table S-1 summarizes the data gaps identified for fuel and cladding, the data to be obtained through the sister rod NDE and DE for application toward a better understanding of the characteristics of HBU fuel, and discussion of how the data could be applied to supporting data gap closure. The sister rod characterization program addresses most of the gaps in understanding HBU fuel irradiation effects, but it is not expected to close all the gaps related to fuel and cladding because the configurations of dry storage systems vary and operational practices vary.

The summary time line for performing the various examinations is provided in Figure S-1. All NDE is expected to be completed by the end of FY 2017, followed by DE (beginning in FY 2018). In FY 2018

selected materials will be shipped to Pacific Northwest National Laboratory for complementary DE, and selected defueled segments will be shipped to Argonne National Laboratory for ring compression testing.

Table S-1. Summary of technical gaps and the examinations planned for the sister rods

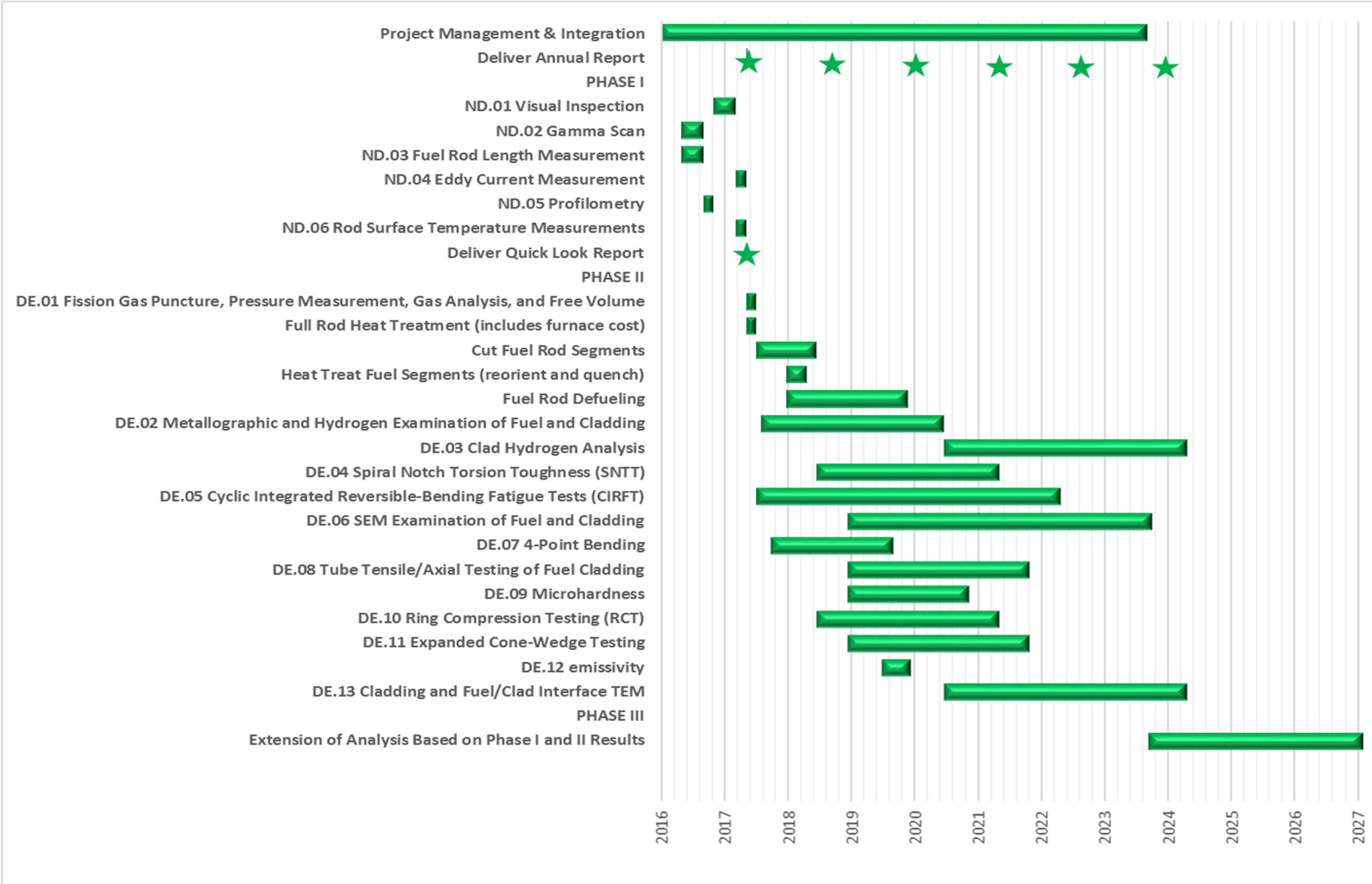
Existing technical gap [2,3,4]	Examination type[note 1]																			Application to gap closure
	ND.01 Visual inspection	ND.02 Gamma scan	ND.03 Fuel rod length	ND.04 Eddy current	ND.05 Profilometry	ND.06 Rod surface temperature	DE.01 Fission gas puncture	DE.02 Metallographic/hydrogen examination of fuel and cladding	DE.03 Clad total hydrogen	DE.04 Spiral notch toughness	DE.05 Cyclic bending fatigue	DE.06 SEM examination of fuel and cladding	DE.07 4-point bending	DE.08 Tube tensile/Axial testing of cladding	DE.09 Microhardness	DE.10 Ring compression tests (fueled and unfueled)	DE.11 Expanded cone wedge	DE.12 Emissivity	DE.13 Cladding and fuel/clad interface TEM	
Stress profiles						X	X			X	X		X	X	X	X	X	X	X	Collected data can be used to understand what stresses and conditions result in fuel rod failure and to better define typical conditions of HBU fuel. The data will be used in conjunction with measurements of forces and stresses imposed on the fuel rod to close the stress profiles gap.
Fuel transfer options										X	X		X	X		X	X			Segments will be heat-treated and allowed to cool to some intermediate temperature before being quenched in water. Data from these examinations will be compared directly with other data collected from the sister rods that were not quenched and can be used to close this gap prior to reopening the RPC.
Drying issues	Retained water in the canister/fuel rod is currently being addressed through the DOE IRP process. Phase III testing with the sister rods can be used to supplement the data if necessary.																			
Burnup credit	Cannot be closed through the sister rod characterization program. A methodology to justify full (actinide and fission product) burnup credit for PWR SNF is provided in ISG-8, Rev 3. Issues to close this gap are related to BWR burnup credit, which cannot be addressed with the current set of sister rods, and to development of a misload analysis approach, which is best addressed with modeling and simulation.																			
Cladding hydride reorientation and embrittlement	X			X			X	X	X	X	X	X	X	X	X	X	X			Comparisons of the results of examinations of corresponding sister rods before and after dry storage can be used to address this gap. The sister rods will be subjected to heat treatments to examine the separate effects related to rod internal pressure and drying temperature to address this gap.
Cladding delayed hydride cracking (DHC)	X			X																Kr-85 monitoring of the RPC is expected to provide an indication if DHC is an issue. Visual examinations/comparisons of corresponding sister rods before and after storage can be used to address this gap. Gap closure will not be available until the RPC cask is opened.
Cladding creep	X		X		X			X							X					Visual examinations/comparisons of corresponding sister rods before and after storage can be used to address this gap.

Table S-1. Summary of technical gaps and the examinations planned for the sister rods (continued)

Existing technical gap	Examination type[note 1]																			Application to gap closure
	ND.01 Visual inspection	ND.02 Gamma scan	ND.03 Fuel rod length	ND.04 Eddy current	ND.05 Profilometry	ND.06 Rod surface temperature	DE.01 Fission gas puncture	DE.02 Metallographic/hydrogen examination of fuel and cladding	DE.03 Clad total hydrogen	DE.04 Spiral notch toughness	DE.05 Cyclic bending fatigue	DE.06 SEM examination of fuel and cladding	DE.07 4-point bending	DE.08 Tube tensile/Axial testing of cladding	DE.09 Microhardness	DE.10 Ring compression tests (fueled and unfueled)	DE.11 Expanded cone wedge	DE.12 Emissivity	DE.13 Cladding and fuel/clad interface TEM	
Annealing of cladding radiation damage								X		X	X	X		X	X				X	Data will be collected from a series of separate effects tests on the sister rods and will be compared with rods from the RPC. The RPC has been strategically loaded to assess annealing damage; however, at the temperatures expected in the RPC annealing damage is not expected to occur.
Fuel fragmentation small particles/aerosols										X	X		X		X					Data will be collected from fuel rod segments breached during testing to address this gap. Aerosolized radionuclide particulates will be collected and measured to address this gap.
Fuel pellet restructuring/swelling	This is a lower-priority gap; no R&D will be performed to specifically address this gap. It is considered a secondary effect that is accounted for in the existing mechanical performance measurements. The data collected through use of actual HBU fuel rod testing can be used to close this gap.																			
Fission product attack on cladding	This is a lower-priority gap; no R&D will be performed to specifically address this gap. It is considered a secondary effect that is accounted for in the existing mechanical performance measurements. The sister rod data collected can be applied to address this gap.																			
Fuel oxidation	This is a lower priority gap. Tests supporting the development of new rate curves for oxidation of the HBU rim can be included in Phase III.																			
Cladding emissivity changes								X				X						X		The sister rod characterization program will collect emissivity measurements from the water side of selected specimens.
Cladding metal fatigue								X			X									Cladding fatigue caused by temperature fluctuations can be evaluated through a comparison of segments that have been thermally cycled with segments that have not been cycled. This gap can be closed prior to the RPC being opened.
Cladding oxidation	X			X				X		X	X	X	X	X	X	X	X			The effects of oxidation can be evaluated through measuring, analyzing, and comparing the DE results for several sister rod samples. This gap can be closed prior to the RPC being opened.

Notes on Table S-1:

1. All examinations are performed at ORNL, with the exception of DE.10, for which 27 3.5 in. segments of defueled cladding will be provided to ANL for testing.



* Note that the dates are contingent on the provision of adequate funding and do not include development/procurement time (as required) for test equipment. Additional time may also be required for hot cell implementation.

Figure S-1. Multiyear examination timeline.

ACKNOWLEDGMENTS

The authors acknowledge and thank the many people who contributed to this report, both those named here and any others who have been a part of this effort. The authors wish to thank Ned Larson, US Department of Energy Office of Nuclear Energy for his support. Also, thanks go to Mike Billone (ANL), Rob Howard (ORNL), and Bob Morris (ORNL) for the expert advice and technical review provided. Finally, many thanks are due to Andrea Beatty and Walter Koncinski for assistance in formatting and preparing the final document.

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REVISION HISTORY

Revision Number	Date Issued	Reason for Revision
0	December 30, 2016	Initial issue

ACRONYMS

4PB	Four point bending test
ADEPT	Advanced Diagnostics and Evaluation Platform
AMBW	AREVA's Advanced Mark-BW fuel design
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
AxTen	axial testing of fuel cladding
BOL	beginning of life (as-manufactured pre-irradiated condition)
BWR	boiling water reactor
CFR	Code of Federal Regulations
CH	contact handled
CIRFT	cyclic integrated reversible bending fatigue tester
CRUD	Chalk River Unidentified Deposits
DBTT	ductile to brittle transition temperature
DE	destructive examination
DHC	delayed hydride cracking
DOE	US Department of Energy
DOE-NE	US Department of Energy Office of Nuclear Energy
ECW	expanded cone wedge
EOL	end of life (condition at the final reactor discharge date)
EPRI	Electric Power Research Institute
ES&H	environmental safety and health
FCT	Fuel Cycle Technologies
FEA	finite element analysis
FEW	fuel element waste
FHT	full-rod heat treatment
FY	fiscal year
GWd/MTU	gigawatt days per metric ton uranium
GT	guide thimble or guide tube
HBU	high-burnup
IFBA	integral fuel burnable absorber
IFEL	Irradiated Fuels Examination Laboratory
IR	infrared
IRP	incident response plan
ISFSI	independent spent fuel storage installation
ISG	interim staff guidance
JAEA	Japan Atomic Energy Agency
KIC	fracture toughness (critical value of stress intensity factor at crack tip)
KID	dynamic fracture toughness
LAMDA	Low Activation Materials Development and Analysis
LOPAR	Westinghouse's low parasitic fuel assembly design
MET	metallographic
µH	microhardness
NAIF	Westinghouse's North Anna improved fuel design
NAIF/P+Z	Westinghouse's North Anna improved fuel design (Performance+ with Zirlo)
NAPS	North Anna Nuclear Power Station
ND	nondestructive
NDE	nondestructive examination
NRC	Nuclear Regulatory Commission

NRR	NRC Office of Nuclear Reactor Regulation
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
R&D	research and development
RCT	ring compression test
RES	NRC Office of Nuclear Regulatory Research
RH	remote handled
RIP	rod internal pressure
RPC	research project cask
RSICC	Radiation Safety Information Computational Center
SEG	segment heat treatment with slow cooling
SEG-REWET	segment heat treatment with water quench
SEM	scanning electron microscope
SET	separate effects test
SNL	Sandia National Laboratories
SNF	spent nuclear fuel
SNTT	spiral notch toughness test
SST	small-scale test
ST	storage and transportation
TBD	to be determined
TC	thermocouple
TEM	transmission electron microscope
TRU	transuranic
UE	uniform elongation
UNF-ST&DARDS	Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System
UQ	uncertainty quantification
UTS	ultimate tensile strength
WDS	wavelength dispersive spectroscopy
WEC	Westinghouse Electric Company
YS	yield strength

POST-IRRADIATION EXAMINATION PLAN FOR HIGH BURNUP DEMONSTRATION PROJECT SISTER RODS

1. INTRODUCTION

Twenty-five high burnup (HBU) (>45 GWd/MTU) fuel rods, summarized in Table 1, were extracted from seven different spent nuclear fuel (SNF) assemblies operated at the North Anna nuclear power plant and were shipped to Oak Ridge National Laboratory (ORNL) in 2016 for detailed nondestructive examination (NDE) and destructive examination (DE). The sister rods include four cladding types: Zirlo, M5, Zircaloy-4 (Zirc-4), and low-tin Zirc-4 (LT Zirc-4). The as-received sister rods are representative of HBU SNF post-operation and pre-dry storage. These HBU fuel rods are "sister rods" to SNF that will be placed in dry storage in a modified TN-32B cask, the research project cask (RPC). The term "sister rod" indicates that these fuel rods[1] have similar characteristics to fuel rods in the RPC because they have been extracted from assemblies with the same design and similar operating histories (symmetric partners) or from the actual fuel assemblies that will be included in the RPC. The planned loading configuration for the RPC is illustrated in Figure 1.

This test plan describes the experimental work to be performed by ORNL for the US Department of Energy (DOE) Office of Nuclear Energy (NE) on the sister rods and serves to coordinate the multiyear experimental program. The data collected will be used in conjunction with the High Burnup Dry Storage Cask Research and Development Project [1]. The work began in fiscal year (FY) 2016 and is expected to continue through FY 2027. The work scope includes the specification of relevant testing, development (as necessary) of required test protocols and fixturing, testing, measurements, data collection and interpretation, and summary reports.

The detailed examinations specified within this plan will provide performance characteristics, material property data, and mechanical performance properties on the sister rods to establish:

- the baseline condition of the HBU SNF rods (the cladding and fuel pellets in situ), pellets, and cladding, post-operation and pre-dry storage;
- changes in HBU rods, cladding, and pellets resulting from dry storage vacuum-drying activities;
- general SNF characteristics data for HBU fuels, including mechanical properties that can be used to expand the applicability of the sister rod data across the industry fleet of casks and to support code validation and future analysis needs prior to the RPC being opened; and
- data from HBU SNF exposed to temperatures higher than those that will be achieved in the RPC to expand the applicability of the dry storage project.

Similar examinations will be performed on HBU SNF rods extracted from the RPC (the "cask rods") at the end of the dry storage period, which may be up to 10 years or longer, to identify any changes that may have occurred during dry storage. The ultimate goal of the work described in this test plan is to provide the data needed to address the technical gaps associated with HBU SNF and long-term storage [2].

[1] With the exception of the Zirc-4 rods taken from assembly F35 and the LT Zirc-4 rods taken from assembly 3A1; these rods are not exact sister rods to any rods in the RPC but were the closest available. Further it should be noted that assembly F35 was operated as a test assembly and was irradiated for 4 cycles of operation to high burnup.

Because this program is expected to be ongoing for a period of 10 years or more, programmatic risks must be recognized and managed to the extent possible. Some mitigating actions aimed at reducing programmatic risk include:

(1) a request for consistent and timely funding, as the program will use specialized facilities and staff for a long period of time and program continuity and institutional memory will be important to maximize the information obtained;

(2) rigorous review and management of ORNL test protocols, sequencing, specimen routing, and specimen tagging because a number of the tests performed are interdependent and complex and there are many small samples; and

(3) timely and periodic revision of this test plan because investigative testing produces new information and data that are expected to highlight previously unidentified opportunities or emerging issues; proposed changes to the test plan and related schedule/cost impacts will be reviewed and approved by the ORNL Project Manager and DOE NE Program Manager prior to implementation.

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 907 / 727 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 983 / 749 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 909 / 729 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 793 / 653 W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 795 / 653 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1039 / 746 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1170 / 754 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1149 / 741 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 977 / 745 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 806 / 668 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 795 / 660 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1162 / 750 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 463 / 397 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1047 / 752 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1152 / 744 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 944 / 718 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 979 / 746 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1159 / 747 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 918 / 724 W	20 0A4 Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 641 / 541 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1163 / 750 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 944 / 717 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 929 / 744 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 912 / 719 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1161 / 749 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1162 / 759 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 989 / 756 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 915 / 721 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 915 / 709 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 970 / 740 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 922 / 738 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 798 / 656 W	

Figure 1. Planned *Research Project Cask* Loading Pattern.

Notes on Figure 1:
Each square represents a basket cell with cell identifier in the upper left corner, and the identifying characteristics of the fuel assembly:

- presence of a thermocouple lance (i.e., TC Lance);
- region reference number (assembly identifier);
- cladding material;
- assembly average burnup;
- initial enrichment (^{235}U weight percent);
- number of cycles operated in the reactor;
- cooling period since discharge at the planned cask loading date; and
- best estimate predicted decay heat at the time of loading and at the end of a 10-year storage period.

Although this test plan only addresses the testing to be performed at ORNL, other organizations expected to perform tests on and/or analytically evaluate the sister rods include, but are not limited to, DOE-NE, Pacific Northwest National Laboratory (PNNL), and Argonne National Laboratory (ANL). Those organizations will provide individual test plans, as needed, to specify their work scope. Interactions are anticipated to share information with the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI). Other stakeholders may be added with the concurrence of the program manager.

Table 1. Twenty-five SNF Rods Selected as Sisters to the RPC rods

Clad material	**Sister rod**		**Cask-stored sister(s)**	
	Donor assembly identifier	***Lattice location***	***Assembly Identifier***	***Lattice location***
M5	30A	G09	57A	I07
M5	30A	K09	57A	I07
M5	30A	D05	57A	E14
M5	30A	E14	57A	D05
M5	30A	P02	57A	B02
M5	5K7	P02	5K6 3K7 5K1	P02
M5	5K7	C05	5K6 3K7 5K1	O13
M5	5K7	K09	5K6 3K7 5K1	K09
M5	5K7	O14	5K6 3K7 5K1	C04
Zirlo	6U3	I07	3U4 3U9 3U6	I07 I11 I11
Zirlo	6U3	M09	3U4 3U9 3U6	E09
Zirlo	6U3	K09	3U4 3U9 3U6	K09
Zirlo	6U3	L08	3U4 3U9 3U6	F10
Zirlo	6U3	O05	3U4 3U9 3U6	C05 O13 C13
Zirlo	6U3	M03	3U4 3U9 3U6	E03
Zirlo	6U3	P16	3U4 3U9 3U6	B02
Zirlo	3F9	N05	4F1 3F6 6F2	N05
Zirlo	3F9	D07	4F1 3F6 6F2	D07
Zirlo	3F9	P02	4F1 3F6 6F2	P02
Zirlo	3D8	E14	5D9 5D5	N13 M04
Zirlo	3D8	B02	5D9 5D5	B16 P16
Low tin Zr-4	3A1	B16	OA4	B16
Low tin Zr-4	3A1	F05	OA4	F05
Zr-4	F35	P17	None (F40)	N/A
Zr-4	F35	K13	None (F40)	N/A

1.1 BACKGROUND

DOE-NE sponsored a gap analysis in support of continued interim dry storage of HBU SNF [2,3,4]. The major gaps identified include:

- the essential mechanical properties as a function of rod burnup, dry storage time, and exposure to temperature cycling (termed "cladding stress profiles"), including clad ductility, modulus of elasticity, Poisson's ratio, ultimate tensile strength (UTS), yield stress (YS), and uniform elongation (UE);
- the effect of cladding hydrides and the effects of hydride reorientation;
- the potential for delayed hydride cracking;
- the effects of annealing and low temperature creep;
- the effects of additional oxidation as a result of retained water in the storage canister;
- the effects of changes in cladding emissivity as it affects the overall temperature profile during dry storage; and
- data supporting computer code validation with appropriate clad/fuel mechanical properties to be used to model SNF rod behavior under normal, off-normal, and hypothetical accident conditions as prescribed by federal regulations [5,6].

In addition to the gaps identified for extended dry storage of HBU SNF, there are three gaps that should be addressed to establish the transportability of SNF:

- Because the rods are subjected to vibrational loads during transportation, it is necessary to establish the fatigue strength and fracture toughness of the HBU rod, along with the effects of rod-to-rod or rod-to-basket impacts resulting from normal transport.
- To substantiate the expectation for normal performance, it is important to understand the role of the fuel in maintaining rod integrity.
- A better understanding of the respirable release rates from HBU SNF is needed to support containment and confinement related assessments.

The data collected in support of the High Burnup Dry Storage Cask Research and Development Project and High Burnup Spent Fuel Data Project are expected to support the closure of most of these data gaps, providing support for extended dry storage and subsequent transportation of SNF that has been irradiated to HBU. More discussion on how the High Burnup Spent Fuel Data Project will address the technical gaps related to extended dry storage and transport of HBU SNF is provided by Hanson [7].

Except as required by agreements with owners of existing data, all scientific and technical information developed or obtained under this project will be made publicly available.

1.2 OBJECTIVES FOR THE SISTER ROD EXAMINATIONS

Information to be collected from the sister rods includes, in priority order:

(1) measurement of the end-of-life (EOL) rod internal pressure for HBU SNF rods, as these data are rare and are key to establishing the cladding stress profiles;

(2) measurement of the essential mechanical properties of the cladding and composite fuel rod at the baseline (post-operation and pre–dry storage) condition for later comparison with dry-stored HBU SNF;

(3) observations of the cladding, or measurement of selected cladding/composite rod mechanical properties, after applying heat loads representative of and/or bounding for the thermal cycling imposed during and following canister loading and drying[2] (the “heat treatment”) for areas with and without Chalk River Unidentified Deposits (CRUD);

(4) measurement of selected cladding mechanical properties after inducing hydride reorientation to assess the effect;

(5) data to understand the effects of expected transportation vibrational loads on the mechanical performance of the composite fuel and clad system;

(6) data on respirable release fractions from HBU fuel measurement of the emissivity of the exterior SNF rod surface for rod locations with and without CRUD; and

(7) synthesis of the data collected to provide empirically-based material property constants and validation information for use in modeling and simulation of other dry storage and transportation scenarios.

The direct comparison of the baseline sister rods with the cask rods and with the heat-treated sister rods will help identify degradation (or recovery) in mechanical performance of the HBU SNF resulting from dry storage. The proposed ORNL sister rod testing addresses all of the identified high-priority and mid-level-priority gaps identified by DOE-NE with the exception of delayed hydride cracking (DHC).

2. PRIMARY TASKS, DELIVERABLES, AND RESPONSIBLE ORGANIZATIONS

The specific NDE and DE to be performed are discussed in Section 3. Testing will be conducted over several years and delineated into separate phases:

Phase I. NDE that began in October 2016; analytical predictions/simulations as needed to support the selection of appropriate test and boundary conditions.

Phase II. Following the NDE, DE to establish baseline data for later comparison with the cask rod and for comparison with heat treated rods; heat treatments to simulate the peak clad temperatures experienced during the dry storage preparation process.

Phase III. As needed, follow-on analyses and/or testing to address observed uncertainties or anomalies or to collect additional data as identified and approved during Phase I or Phase II.

Phase IV. Cleanup and waste material disposal.

Phase I will be performed first and will be concluded with a report of the NDE performed and any findings or recommendations. A preliminary “quick-look” post-irradiation examination (PIE) report will be made available soon after the rods have been examined to allow for reevaluation of the cutting plans prior to initiating the Phase II DE. Concurrently with the NDE, pre-test predictions to assist in the design of the experiments and post-test verification of measurements will be performed as appropriate. The primary

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[2] During the vacuum drying process heat transfer from the SNF is limited and the temperature of the SNF rods increases. Typically, after drying and helium backfill is complete the SNF rod temperatures continue to increase as the heat load redistributes within the canister/cask until the system reaches thermal equilibrium with the environment. Analytical simulations indicate that peak SNF cladding temperatures during heat load redistribution are the highest temperatures that occur during the dry storage lifetime. Because the in situ drying process imposes relatively high temperatures, the cladding in particular can undergo several changes in stress state and metallurgical conditions.

purpose of the predictions is to enable design and optimization of experimental configurations to ensure applicability for intended use.

Following Phase 1, Phase II will begin. Phase III and IV activities may be completed concurrently with or following Phase II. Prior to segmenting the sister rods for mechanical testing, all rods will be punctured at ORNL to obtain the rod internal pressure measurement. Sister rods selected for PNNL testing will then be shipped. Sister rods selected for heat treatment will be moved to the heat treatment furnace (one at a time), and the prescribed temperatures will be imposed (see Section 3.3.1 for more discussion) prior to puncture and segmentation. Several sister rods will be set aside for future use. The remainder will be cut into short segments for particular tests as specified in Appendix A. After segmentation, selected segments will be defueled as needed to perform the desired mechanical testing. Twenty-seven defueled segments will be sent to ANL.

Most of ORNL's sister rod examinations will be performed in the ORNL Irradiated Fuels Examination Laboratory (IFEL) Building 3525 hot cell bank. When necessary, defueling will be performed at the ORNL radiochemical analysis laboratory. Small sections of cladding that have a low enough activity may be examined at the 3025E facility and the ORNL building 4508 LAMDA laboratory.

Detailed procedures for the examinations will be available prior to the performance of the examination and will be approved before use by the ORNL project manager. Work will be performed in accordance with the Fuel Cycle Technologies (FCT) quality assurance plan [8] and all work will be done under the appropriate facility environmental, safety, and health (ES&H) guidelines.

The tasks and examinations will be conducted taking into consideration data priorities and in an order that is most efficient for the hot cell as approved by the ORNL project manager.

Key milestones/deliverables include:

(1) video and images of the external surface of the sister rods (Phase I);

(2) a preliminary NDE report (Phase I);

(3) final rod segmenting plan that incorporates the data collected during Phase I (prior to beginning Phase II);

(4) a final comprehensive NDE report (prior to the end of Phase II);

(5) annual Phase II progress reports summarizing the progress of the testing (no test results) based on milestones and schedule;

(6) revised or supplementary test plans (as necessary) integrating any Phase III follow on testing (prior to beginning any Phase III examinations);

(7) periodic reports summarizing the accumulated results of each primary DE area (Phase II and Phase III); and

(8) a final comprehensive report summarizing all NDE and DE and providing the primary conclusions reached by the study (within 1 year of the end of Phase II and III).

It is anticipated that the research and development (R&D) debris wastes will be disposed of at the conclusion of various tests and as sufficient volumes of waste are generated. Some DE samples may be stored after testing until appropriate data analyses have been completed and it has been determined that the samples are no longer needed. ORNL will be responsible for dispositioning waste from sister rods examined at ORNL; PNNL and ANL will be responsible for sister rod materials allotted to them, including the disposition of any waste generated by their examination.

The ORNL UFS team is responsible for executing the work identified in this plan, and the work will be performed by selected experienced personnel throughout the ORNL complex.

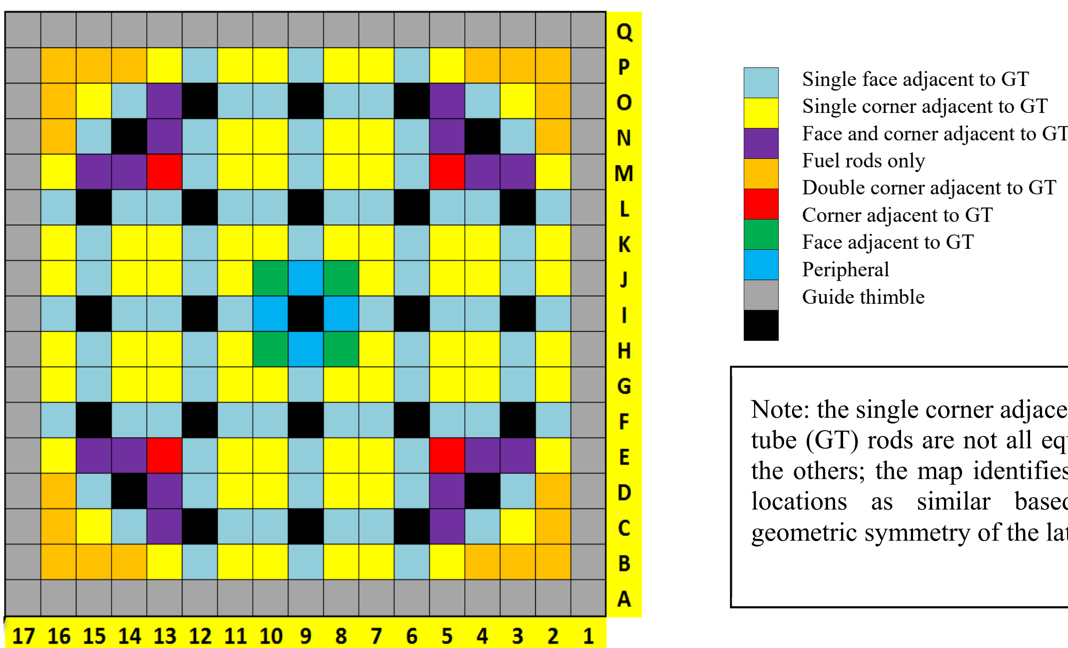
3. SCIENTIFIC APPROACH AND EXAMINATION METHODS

This section describes each of the primary tasks discussed in Section 2. Subtasks and associated descriptions are also provided and correspond to elements listed in the program. A Gantt chart to illustrate the schedule, approximate task durations, and how the tasks fit together is included as Appendix B. The Gantt chart is subject to change as the work proceeds to capitalize on unanticipated opportunities, react to and overcome unforeseen difficulties, and accommodate new and/or more accurate information (e.g., greater clarity in cost and schedule information) as it becomes available.

3.1 TEST CONDITIONS AND ROD NOMENCLATURE

During Phases I, II, and III, unless otherwise specified, examinations will be completed at ambient temperature at standard pressure in air, including those using heat-treated specimens. For those tests conducted at ambient conditions, as a minimum, hot cell temperature will be measured and recorded for each test day near the location of the test activity. Several tests will be completed at a range of temperatures, and the conditions of the test (ambient and specimen temperature, fill gas, pressure) are specified within the test matrix. For these tests, all specified test conditions will be actively monitored and recorded during the test.

A summary of the fuel rods to be destructively examined by ORNL is provided in Table 2. Additionally, for information, Table 1 and Table 2 list the cask rods paired with each sister rod for direct post-storage comparisons. Throughout the remainder of this document the sister rods will be described using the format XXXYYY, where XXX represents the fuel assembly ID and YYY represents the rod lattice position within the assembly, as illustrated in Figure 2. Figure 2 is color-coded; the colors denote the theoretical lattice positions within a typical fuel assembly where symmetric conditions may exist. "Segment" is used to denote the rough cut segment of the sister rod and "specimen" is used to indicate a segment or parts of a segment that have been further modified, sectioned, or otherwise prepared for testing.



Note: the single corner adjacent to guide tube (GT) rods are not all equivalent to the others; the map identifies these rod locations as similar based on the geometric symmetry of the lattice.

Figure 2. Fuel assembly lattice map with sister locations identified.

The draft cutting plan provided in Appendix A allocates rough cut segments from each sister rod for the initial Phase II testing. Individual sister rod segments are described using the format XXXYYYRRRRTTTT where XXXYYY is the sister rod ID as previously described, RRRR is the lowest original rod elevation of specimen, and TTTT is the upper original rod elevation of the segment. If segments are subdivided to provide additional test specimens, the ID is further adjusted to reflect the rod elevations originally occupied by the specimen. This nomenclature is intended to provide traceability to sister rod and the elevation on the sister rod where each specimen originated.

Several specimens are allocated from each sister rod to establish the rod average condition as a function of axial location with respect to clad oxide layer thickness and hydride content, metallographic structure, and fuel condition and structure. For selected examinations, both pre-storage and post-storage mechanical DE includes examinations of total hydrogen content, hydride density, and orientation, as these can have a profound impact on the examination results. This is particularly important for heat-treated specimens. For dynamic DE performed with fueled segments, the experiment will be designed, as possible, to allow for collection of aerosolized radionuclides released on fracture.

Table 2. Sister rods selected for destructive examination at ORNL

Clad material	Donor assembly identifier	Sister rod lattice location	Assembly average burnup (GWd/MTU)	Assembly operation	Key characteristics	Cask-stored sister(s)	
						Assembly identifier	***Cask rod lattice location***
M5	30A	G09	52.0	30A was operated hot-hot-cold. Its last cycle was uprated in the last quarter, making it the cycle with the highest power density of those represented. This assembly had the highest pellet enrichment. The assembly design included mid-span mixing grids which should have lowered the rod operating temperature in the hot spans somewhat. All of the M5 rods are expected to have relatively low rod internal pressure and cladding hydrogen content.	Sister rod to assembly rod in assembly 57A lance position with close proximity to the peak (hottest) cask rod position (I-7). The rod was operated in a GT adjacent location. Of the sister rods, predicted to have the highest decay heat.	57A	I07
M5	30A	K09			The corresponding cask rod is next to a lance position with close proximity to the peak (hottest) rod position (I-7) in the cask	57A	I07
M5	30A	D05			D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons. Because the poisons influence power output during irradiation, the rods are expected to have different characteristics, even though they have burnups that are similar	57A	E14
M5	30A	E14				57A	D05
M5	5K7	O14	53.3	5K7 was operated hot-hot-cold and also had the highest pellet enrichment of the assembly batches represented. The assembly design included mid-span mixing grids, which should have lowered the rod operating temperature in the hot spans somewhat.	Approximately average assembly burnup; the rod was operated in a GT diagonal location. All of the M5 rods are expected to have relatively low rod internal pressure and cladding hydrogen content.	5K6 3K7 5K1	C04
Zirlo	6U3	I07	52.7	6U3 was operated hot-cold-cold. All of the 6U3 sister rods are expected to have relatively high rod internal pressure and cladding hydrogen contents.	This rod is a sister to three different fuel assemblies in the central, middle, and outer regions of the RPC basket. The rod was operated in a GT adjacent location.	3U4 3U9 3U6	I07 I11 I11
Zirlo	6U3	M09			This rod's cask sister is next to a lance position	3U4 3U9 3U6	E09
Zirlo	6U3	K09			This rod's cask sister is next to a lance position	3U4 3U9 3U6	K09

Table 2. Sister rods selected for destructive examination at ORNL (continued)

Clad material	Donor assembly identifier	Sister rod lattice location	Rod average burnup (GWd/MTU)	Assembly operation	Key characteristics	Cask-stored sister(s)	
Zirlo	3F9	N05	52.3	3F9 was operated hot-hot-cold. Both sister rods appear to have experienced grid-to-rod fretting in reactor; marks were observed at grid locations along the entire axial length. The 3F9 rods are expected to have moderately high rod internal pressure and cladding hydrogen content.	Rod is a good match for several cask rods with a relatively high burnup.	4F1 3F6 6F2	N05 N05 N05
Zirlo	3F9	D07			Rod having approximate average assembly burnup	4F1 3F6 6F2	D07
Zirlo	3D8	E14	55.0	3D8 was operated hot-cold-cold. The 3D8 rods are expected to have moderate rod internal pressure and high cladding hydrogen content.	Rod having approximate highest burnup in assembly and the highest sister rod burnup.	5D9 5D5	N13 M04
Zirlo	3D8	B02			Rod having close to lowest burnup in assembly (selected based on pulling restriction).	5D9 5D5	B16 P16
Low tin Zr-4	3A1	B16	50.0	3A1 was burned hot and in only two cycles reached high burnups comparable to the other sister rods.	Rod having lowest burnup in assembly; close to assembly periphery	OA4	B16
Low tin Zr-4	3A1	F05			Rod having highest burnup in assembly; reasonably close to center of assembly. Areas of CRUD observed.	OA4	F05
Zr-4	F35	P17	57.9	Four cycles of operation. F35 operated its fourth cycle in D-bank with control rods partially inserted. Operated prior to North Anna's power uprates so lower power density. Lowest enrichment. At time of exams, predicted to have the lowest decay heat.	Rod located on the assembly periphery. Spalling oxide was observed. This rod is expected to have a high rod internal pressure combined with a relatively large cladding hydrogen content.	None (F40)	N/A

3.2 PHASE I: NONDESTRUCTIVE INTACT ROD EXAMINATIONS

The Phase I PIE work will be performed in the ORNL IFEL hot cell bank. The major emphases of the NDE tasks are visual examinations of the rod external surfaces and gross dimensional measurements. Detailed procedures for the NDE work will be available prior to the performance of the examination and will be approved before use.

The goal of the NDE task is to experimentally verify the presence or absence of cladding degradation in the non–dry stored test fuel and to provide characterization information for comparison with post–dry storage conditions. Observations will include:

(1) visual and dimensional inspections and reporting any physical abnormalities (e.g., chemical attack, blisters, cracks, heavy or uneven oxide layers, weld failures, or clad distortions) and a digitally created user-viewable montage of each rod;
(2) gamma scanning to nondestructively
    a. obtain relative axial burnup profiles,
    b. identify any gross migration of fission products or large pellet cracks,
    c. identify any pellet stack gaps,
    d. to measure the pellet stack height, and
    e. to identify location and magnitude of any burnup depressions due to grid spacers;
(3) Eddy current scans to obtain information on clad mechanical macroscopic defects; and
(4) Rod surface temperature measurements.

These tasks will be conducted in an order that is most efficient for the hot cell. A preliminary “quick-look” PIE report will be made available after the rods have been examined but prior to complete analysis so that the destructive PIE planning can be conducted in a timely manner. A comprehensive NDE report will be prepared following completion of all NDE tasks.

All 25 of the sister rods (listed in Table 1) will be examined using ORNL’s Advanced Diagnostics and Evaluation Platform (ADEPT). The ADEPT system, shown in Figure 3 with selected testing equipment, allows for efficient inspection of the rods for anomalies and dimensional characteristics. The planned NDEs are listed in Table 3, and the following sections provide a more detailed description of each task. Prior to further sample preparation, rod shipment to other laboratories, or segmentation, the NDE data will be evaluated to determine if additional NDEs are necessary and any required additional examinations will be completed prior to any DE of the rods.

3.2.1 ND.01: VISUAL INSPECTION

This examination will be conducted by placing each fuel rod on the ADEPT inspection apparatus and a high resolution camera to view the exterior of the rod under ambient lighting conditions. The fuel rod will be examined in a systematic manner by moving an axial region of the rod into the camera field of vision and rotating the rod so it can be photographed at all angles. This will be done all along the length of the rod so that the surface of the rod is completely imaged. A digitally created user-viewable montage of each rod will be assembled. Regions of interest can be looked at more closely; images of regions clearly indicating damage will be flagged for further analysis. Work on the rod may be suspended until the cause and impact of the damage is determined (i.e., spontaneous or induced during handling).

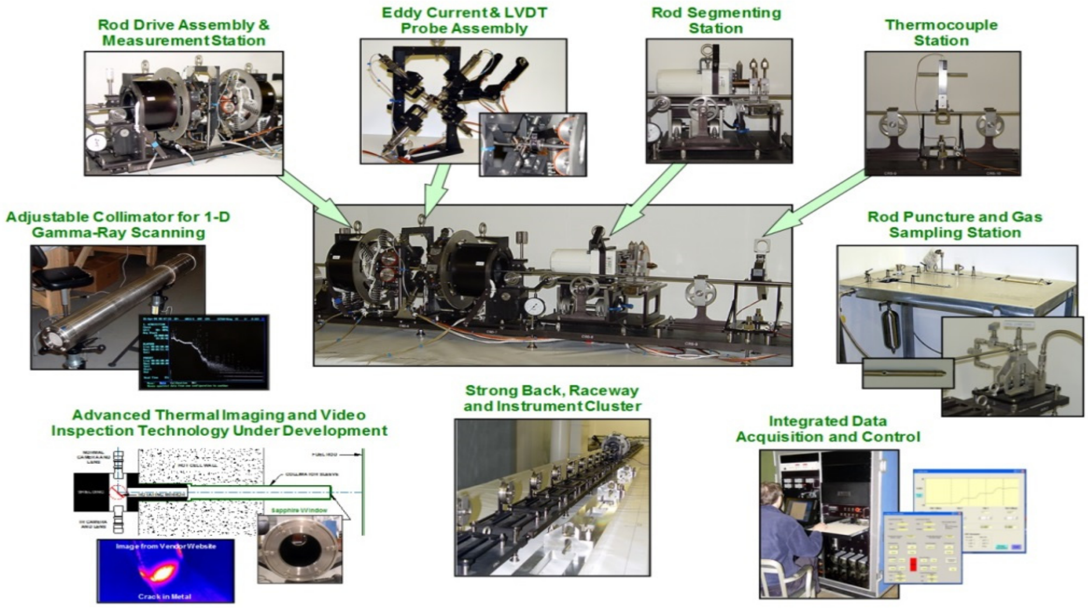


Figure 3. ORNL's ADEPT spent fuel rod handling and measurement system, including select associated equipment for performing testing.

Table 3. Nominal nondestructive examinations

Test No.	Examination	Number	Examination description
ND.01	Visual inspection	1 per rod 25 total	Verify that the fuel rods are sound and undamaged. Note any CRUD or cladding damage/wear marks. Digitally stitch a series of photographs together to create a user-viewable montage of the entire rod.
ND.02	Gamma scan	1 per rod 25 total	Measure relative activity as a function of axial position, determine pellet stack height, and note any gaps between pellets. Note flux (burnup) depressions due to grid spacers.
ND.03	Fuel rod length measurement	1 per rod 25 total	Measure rod length, noting the as-discharged in-reactor rod growth. This measurement provides the initial condition for later comparisons relative to cladding creep and growth.
ND.04	Eddy current measurement	1 per rod 25 total	Note any clad flaw (cracks, holes, other anomalies). Cladding oxide thickness and cladding hydrogen content as a function of axial elevation may be measured, depending upon the availability of necessary standards and probes.
ND.05	Profilometry	1 per rod 25 total	Measure the rod diameter as a function of axial position. Note average diameter, out-of-roundness, and any unusual features.
ND.06	Rod surface temperature	5 per rod minimum, 125 total	Measure the surface temperature of each rod at selected positions along the rod axis. This information is needed to confirm heat treatment simulations and to provide the initial set points for the heat treatment systems.

3.2.2 ND.02: GAMMA SCAN

Each rod will be 1D gamma-scanned (resolution of ~1 mm) using ADEPT. The rod will be moved in front of a collimated detector, and the activity as a function of rod length will be recorded. Three items will be of specific interest: the activity profile along the rod, the inferred fuel stack height, and the presence of any gaps or irregularities in the fuel stack. In addition, any gross migration of fission products will be noted. If any serious abnormalities are found, that information will be flagged for further analysis. Work on the rod may be suspended, depending on the nature of the observed problems.

3.2.3 ND.03: FUEL ROD LENGTH MEASUREMENT

The axial length of each rod will be measured using ADEPT primarily to infer irradiation growth.

3.2.4 ND.04: EDDY CURRENT MEASUREMENT

Each rod will undergo an eddy current scan using the ADEPT to determine and locate any macroscopic cladding flaws. Ideally, the resolution should be sufficient to find pinhole-type flaws; the actual flaw size resolution will depend on the hardware available. If any serious abnormalities are noted, that information will be flagged for further analysis. Work may be suspended on the rod, depending upon the nature of the problem (e.g., accounting for ferromagnetic interference). Because the clearance between the sensor coil and the rod is small, any serious rod deformations can prevent the rod from being measured, and some rods may not be scanned. Also, as possible, the oxide thickness and/or hydrogen content will be measured as a function of axial elevation using eddy current measurement techniques.

3.2.5 ND.05: PROFILOMETRY

Profilometry will be conducted by both axial and angular movement of the rod and will be indexed to the other nondestructive measurements. A modest clearance is required between the sensors and the rod, so large rod deformations or defects may be out of measurement range, and it may not be possible to measure some segments of a deformed rod. Software reconstruction of the rod's cross section may be pursued if initial measurements indicate that it is significantly out of round.

3.2.6 ND.06: ROD SURFACE TEMPERATURE MEASUREMENT

The surface temperature axial profile of each rod will be measured at a minimum of five selected elevations to provide design and initial condition data for the heat-treatment applications (see Section 3.3).

3.3 DESTRUCTIVE EXAMINATION SAMPLE PREPARATION

The goal of the destructive PIE task is to define the mechanical properties of interest for gap closure (see Table S-1) for HBU SNF fuel/cladding and to better understand the mechanical performance of the composite fuel and clad system. These mechanical properties will vary based on cladding type, burnup, oxide and crud layer thicknesses, hydride content and orientation, radiation damage, annealing, and temperature. Testing will include separate effects tests (SETs) and small-scale tests (SSTs). Not every rod will be subjected to the full suite of DEs; some rods will be used to perform specific kinds of tests.

Some of the activities within this primary task are not performed routinely, and/or they need to be implemented with irradiated materials in a hot cell, so they have uncertainties and risks related to cost, schedule, and measurement outcome. ORNL will closely coordinate DE to ensure that all examinations follow well-documented procedures and are conducted so that resulting data can be readily compared. Hence, the DE includes activities that require detailed planning, decision making, and authorizations.

Segments will be taken from the available fuel rods as directed by the Appendix A cutting plans (as amended following NDE). The scope of the DE may be adapted as appropriate to capitalize on potential opportunities for cost/schedule sharing with other programs.

Phase II PIE work will consist of DEs delineated into two major subtasks:

(1) destructive analyses to provide baseline characteristics data for rods in the RPC for future comparisons against and

(2) destructive analyses

   a. to provide useful information for comparisons of properties after drying and

   b. to provide general SNF characteristics data for HBU fuels, including mechanical properties that can be used to expand the applicability of the data across the industry fleet of casks of higher temperatures and to support computer code validation and future analysis needs prior to the cask being opened.

The samples are prepared for DE using a combination of processes, including heat treatments, cutting, and defueling (selected samples). Heat treatments are applied both before (i.e., to full-length rods) and after segmentation and are described in Section 3.3.1. The segmentation process is described in Section 3.3.2, and draft cut diagrams with DE segments identified for each rod are provided in Appendix A. The defueling process to be used is described in Section 3.3.3.

3.3.1 HEAT TREATMENTS TO BE APPLIED TO SELECTED RODS AND SPECIMENS

Phase II heat treatments address technical gaps related to the effects of temperature and time during dry storage, particularly by producing specimens for DE which have experienced prototypical peak cladding temperatures. For extended dry storage there are three time frames of interest:

- T0: The "baseline" condition corresponding to the condition of the fuel prior to any dry storage activities. No heat treatments are applied, and the specimens are tested in the as-received condition.
- T1: Corresponding to the time when the fuel reaches its highest temperature. Heat treatments are applied to allow an understanding of the physical changes that occur in the fuel rod cladding during the heating phase and subsequent cooldown phase. The nomenclature used to describe the specimen type, heat treatment range, and cooling conditions to be applied include the following:
  - Full-rod heat treatment (FHT): The full length of the intact (unpunctured) sister rod will be subjected to the heat treatment; fuel rods will be held at temperature for a specified length of time (to be determined) and allowed to cool to steady state at ambient hot cell conditions.
  - Segment heat treating with relatively slow laboratory cooling (SEG): Multiple-use segments cut from the sister rod after puncture will be repressurized and subjected to heat treatment with a representative slow cooling rate applied following the heat treatment; the rod internal pressure and temperature of the heat treatment may vary, depending upon the objectives of the test and will be specified for each specimen.
  - Segment heat treatment with water quench (SEG-REWET): Multiple-use segments cut from the sister rod after puncture will be repressurized and subjected to heat treatment followed by a rapid quench in water to room temperature; the rod internal pressure and temperature of the heat treatment may vary, depending upon the objectives of the test and are specified for each specimen.
- T10: Corresponding to the end of the RPC demonstration, following dry storage of the cask rods at the North Anna site and transportation of the cask with its fuel assemblies and cask rods to a DOE examination facility. All T10 data will be derived from the cask rods.

The T0 nomenclature always indicates segments that have not been heat-treated and are tested in the as-received condition (after puncture and segmentation). The T10 nomenclature is reserved for the cask rods and is therefore not used in the sister rod test plan.

The following sections provide a more detailed description of the planned heat treatments. All heat treatments are conducted in a dry environment (inert gas purge, dry air, or dry nitrogen), with the exception that the SEG-REWET protocol includes a final quench in a water bath at representative SNF pool temperature.

3.3.1.1 FHT: FULL-ROD HEAT TREATMENT

Many of the technical gaps to be addressed by the High Burnup Spent Fuel Data Project and the Dry Storage Cask Research and Development Project are tied to the temperatures of the SNF during dry storage. As discussed in Section 1.2, an objective of the sister rod examinations is to observe any changes in the SNF rod response resulting from elevated SNF temperatures that occur during dry storage. The goal of the FHT is to apply the peak temperature to the sister rod in the same axial temperature profile expected in a dry storage cask. Past applications of heat have been limited to short pressurized defueled cladding segments. A more prototypical condition can be achieved by heating full-length rods prior to puncture. This approach preserves the as-received SNF rod internal pressure, producing prototypical cladding hoop stress distributions along the entire length of the rod. Additionally, the FHT method provides time and cost efficiencies and reduces uncertainties introduced during heat treatment of short segments that are individually sealed, pressurized, and heated.

There are two avenues for selection of FHT peak temperatures and axial profiles for application to the sister rods: (1) use the RPC measurements; (2) use analytical predictions to select appropriate conditions. However, even though the RPC was aggressively loaded with HBU SNF, the RPC SNF temperatures are expected to be well below the regulatory limits for peak cladding temperature. Best-estimate thermal calculations available from the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) [9] estimate the maximum peak temperature reached in dry storage (based on available dry storage cask systems modeled to date [~33% of current inventory]) for the current SNF inventory is 325°C while current predictions for the RPC expect a peak cladding temperature of 271°C [10]. Thus, to ensure a conservative realistic peak temperature for the sister rod examinations, the UNF-ST&DARDS estimated maximum peak temperature is selected. The temperature distribution along the axis of the SNF rods in a dry storage system is dependent primarily on the system design and there are many potential variations. For simplicity the expected measured RPC axial profile (based on measurements during RPC loading) will be imposed on the sister rods during the FHT.

It is noted that the Zirc-4 clad rods from assembly F35 are not typical HBU Zirc-4 SNF rods, as they were operated for four cycles to HBU in a test assembly. Application of the UNF-ST&DARDS estimated maximum peak to the F35 sister rods is therefore expected illustrate bounding realistic results for Zirc-4 cladding.

The duration of the FHT heat treatment is anticipated to be consistent with the planned RPC thermal stabilization period (estimated as 3 days and up to 2 weeks); after heat treatment, the rods will be allowed to cool at a relatively slow laboratory rate (approximately 5°C/hr) at ambient temperature to equilibrium prior to initiating DE. Measurement of the rod internal pressure (either directly or indirectly) during FHT is not planned. As possible, the inert gas purge from the FHT furnace will be monitored during heat treatment to identify any indications of rod breach during the heat-treatment protocol.

Two sister rods are currently reserved as backups for the three primary FHT rods. The backup rods may be used to investigate another peak cladding temperature and/or axial temperature profile, other cooling conditions, or other holding times, pending the results of the primary FHT sister rod examinations. Additional investigations, such as the effect of higher RIP related to integral fuel burnable absorber (IFBA) rods, are also planned using SEG heat treatments (see Section 3.3.1.2), assuming that an appropriate reference for IFBA RIP becomes available.

Table 4 summarizes the FHT heat-treatment application and samples.

Table 4. Summary of FHT heat treatment application and samples

Objective	Mimic predicted dry storage system peak clad temperatures representative of the dry storage system fleet. Fuel rods will be held at temperature for 3 to 14 days (depending upon the RPC measurements) followed by slow cooling (5°C/hr) to ambient conditions.
Initial conditions	Unpunctured, fueled
Sample size	Full-length rod
Samples	3 (F35P17, 3D8E14, 5K7O14); peak temperature to be applied based on past cask loading maximum peak cladding temperature of 325°C in the axial profile measured in the RPC.
Reserved backup samples	2 (3F9D07, 3D8B02) One or both of these rods may be used to simulate other conditions (particularly peak temperatures) pending the results of the primary FHT rod examinations.
Information or benefit obtained	The T1 condition will not be available from RPC rods because the cask rods will not be destructively examined at T1; thus the SEG, SEG-REWET, and FHT rods must provide the sum of information on the separate effects related to the peak thermal cycling.
Prerequisites	NDE rod prep (1 to 6)

The sister rods selected for the FHT heat treatment were chosen based on two main criteria: the likelihood of a relatively high amount of hydrogen in the cladding and the predicted rod internal pressure. Past testing at ANL has identified these two parameters as important to hydride reorientation, which can degrade the load-bearing capability of the cladding under some conditions. Since the rod internal pressure is not correlated to cladding oxidation and hydrogen pickup, the rod having the highest pressure is not necessarily the rod whose cladding has the highest hydrogen content. Specimen selections are based on analytical predictions using the operating data available for the sister rods. One rod of each cladding type (M5, Zirlo, and either Zirc-4 or low-tin Zirc-4) was selected for the FHT heat treatment, and two additional rods (one M5 and one Zirlo) are reserved without puncture pending the results of the initial testing.

The heat-treated rods will be segmented per the cutting plan given in Appendix A, and selected segments will be subjected to destructive testing as listed in Section 3.3 for comparison with the T0 benchmark test results.

3.3.1.2 SEG: SEGMENT HEAT TREATMENT WITH SLOW COOLING

A summary of the SEG heat treatment application and samples selected is provided in Table 5. Fuel segments will be heat-treated to conservative temperatures (see FHT heat treatment), and/or to temperatures/pressures large enough to induce hydride reorientation, and then cooled at a relatively slow laboratory rate (approximately 5°C/hr). Several heating and cooling cycles may be applied to a segment to assess the impact of multiple heat-up/cooldown cycles.

For the purpose of segment repressurization, fueled segments will be fitted with end caps and will be pressurized to the specified rod internal pressure for the DE, nominally the rod pressure measured for the sister rod during puncture (DE.01), using an argon, nitrogen or helium fill gas. Defueled segments may use swage-locked end caps and will also be repressurized using an inert gas. In the case of ring compression tests (DE.10), other pressures may be specified as needed to achieve test objectives; for example, to encompass expected pressures for rod types other than those contained in the RPC such as Zirlo-clad rods with integral fuel burnable absorber (IFBA). Long segments may be heat-treated and then cut into smaller specimens for DE. It is notable that the welding process can introduce some distortions and heat affected zones. Past experience with the welding process indicates that the weld melt region is approximately 6.35 mm wide (in the axial direction of the rod), very little distortion is introduced, and microstructural changes are limited to a region ±19 mm of the weld centerline for a single pass weld. Multiple weld passes can result in unacceptable distortion. Mechanical tests using welded specimens will be specified such that the heat affected zones are located outside of the test gauge section, and will implement an inspection for distortion prior to heat treatment and after heat treatment for acceptance of the specimen for testing. The distortion acceptance criteria are expected to be particular to each test method and will therefore be specified with the test protocol.

The intent of the SEG heat treatment is to develop a cladding morphology similar to that encountered for a full length fuel rod under the same environmental conditions. However, there are artifacts that can be introduced to the specimen by the SEG heat treatment. For example, it is possible, given the short length of the SEG segments in conjunction with the relatively large solid alloy end plugs, that hydrogen will migrate from the test segment to the end plugs, creating a lower hydrogen test specimen that is not representative of the full length fuel rod cladding morphology. The amount of hydrogen lost to the end plugs depends on the heat treatment target temperature, the hold time at temperature, the temperature differential between the end and the body of the segment, the mass ratio of the end plug and the segment, and the initial hydrogen solution concentration in the segment at the target temperature. Also, for fueled test segments, it is possible to disrupt the interface between the cladding and pellet when the segment is re-pressurized, and recent experimentation appears to indicate that the cladding/pellet interface is an important component of the rod mechanical performance [16]. To avoid damaging the cladding/pellet interface on fueled test samples, the pressure applied during the heat treatment should be limited to less than that measured for the rod during DE.01, rod puncture, unless other calculations or information can demonstrate that damage of the cladding/pellet does not occur.

One of the goals of the SEG examinations is to compare the results of full length heat treatments to the results obtained using short pressurized segments. To provide a comparison of the results of SEG and FHT methods, initially, a few segments are allocated for SEG examinations (excluding those allocated for DE.10). The results of examinations of segments that undergo the SEG heat treatment will be compared with similar FHT segments and comparable T0 segments. Also, two SEG specimens (1 M5 and 1 ZIRLO), post mechanical test, will be sectioned and metallographic (DE.02) and total hydrogen measurements (DE.03) will be taken as a function of the axial location to determine if significant hydrogen migration occurred during specimen preparation. If differences are observed, more examinations may be specified using reserved materials. The initial subset selections are annotated in the cutting plan found in Appendix A.

Table 5. Summary of SEG heat-treatment application and samples

Objective:	Mimic predicted dry storage system peak clad temperatures. Fuel rods segments are repressurized and are expected to be held at temperature for up to 3 days to closely mimic realistic conditions (as gauged by the RPC measurements) followed by slow cooling (5°C/hr) to ambient conditions.
Initial conditions	Punctured, segmented, fueled or defueled segments
Sample size	Per the individual DE to be performed, 1 to 6 in.; see cutting plan. Longer segments may be used for heat treatment and cut a second time for a more economical heat-treatment cycle.
Samples	Up to 41 segments from 6 T0 rods, including 27 ANL RCT specimens. Tests may be expanded or eliminated based on initial segment test results. (3F9N05, 6U3M09, 6U3I07, 3A1B16, 30AD05, 30AG09, 30AE14)
Reserved backup samples	Available from the 3 backup T0 rods
Information or benefit obtained	The heat treatment imposed is meant to bound the postulated T1 conditions for the current US commercial SNF inventory. Minimal mechanical testing will be completed, and the results will be compared with results for T0 and other T1 specimens.

	The T1 condition will not be available from RPC rods because the cask rods will not be destructively examined at T1; thus the SEG, SEG-REWET, and FHT rods must provide the sum of information on the separate effects related to the peak thermal cycling.
	As possible, during SEG heat treatments the rod surface emissivity will be measured.
Prerequisites	NDE and segmentation; end cap welding and pressurization

Different segments may be heat-treated to different temperatures and may be cycled through the temperature range more than once (upper temperature limit of 400°C consistent with previous studies [11,12]). The heat-treated segments will be subjected to destructive testing as listed in Section 3.3 for comparison with T0 and other T1 test results. The results may also be compared with the FHT results to validate the segmented heat treatment as an acceptable approach.

3.3.1.3 SEG-REWET: SEGMENT HEAT TREATMENT FOLLOWED BY SLOW COOLING AND QUENCH

A summary of the SEG-REWET heat treatment application and selected samples is provided in Table 6. As discussed in the SEG heat-treatment section, fuel segments will be heat-treated to dry storage system peak cladding temperatures that are conservative for the current US commercial SNF inventory and may also be subjected to higher temperatures and cycled to produce hydride reorientation. However, rather than cooling slowly as for the SEG heat treatment, the SEG-REWET segments will be relatively slowly (approximately 5°C/hr) cooled to an intermediate temperature (still to be determined) and then quenched in a water bath (at typical spent fuel pool temperature). The SEG-REWET segments will be pressurized to the measured rod internal pressure of the parent rod or similar FHT rods. The water bath will be representative of US spent fuel pool conditions, although the bath volume and chemistry will be subject to existing facility constraints. Note that the process represented by this test is different than what is currently used in France and Sweden where fuel is routinely transported after a much shorter cooling time (i.e. 1-2 yrs.) before being rewet. Specific temperatures and identification of facility constraints will be documented as supporting modeling and simulation evaluations are completed.

The SEG-REWET treatment is postulated as bounding the heat/quench conditions for transfer of bare fuel from dry storage (e.g., at a consolidated storage facility) where the fuel is placed back into a pool before being repackaged. Selected segments will be heated to achieve peak cladding temperature ranges expected from a minimum of five-year cooled fuel (based on 10 CFR 961 standard fuel specifications). The experimental boundary conditions to be applied will be specified based on best-estimate input parameters and cross-checked with existing cask certificates of compliance to ensure that it is representative of fuel that is capable of meeting both thermal and dose requirements for transport in a bare fuel cask.

As mentioned previously, welding, heating, and pressurization for test specimen preparation can introduce artifacts that aren't representative of an in situ SNF rod. Similar to the requirements established for the SEG specimens, the SEG-REWET specimens will be inspected for distortion after end cap welding, both before and after heat treatment, and all tests utilizing welded specimens will ensure that heat affected zones are outside of the test gauge section. Pressurization is limited to that measured during puncture for the selected rod, and two specimens (1 M5 and 1 ZIRLO) will be sectioned axially to determine if significant hydride migration occurred DE.02 and DE.03) post-mechanical test.

The SEG-REWET specimens will be subjected to destructive testing as listed in Section 3.3 for comparison with T0 and other T1 test results. Initially, only a few segments are allocated for SEG-REWET examinations. If no difference in the visual or mechanical examination results are observed between segments that undergo the SEG-REWET heat treatment and comparable untreated segments, no further SEG-REWET examinations will be conducted. However, if a difference is observed, more examinations may be specified using reserved materials. As noted for preparation of SEG specimens, unintended artifacts can be introduced to the specimen by the heat treatment itself and one SEG-REWET post-test specimen will be selected for axial total hydrogen measurements (DE.03). The initial subset selections are annotated in the cutting plan found in Appendix A.

Table 6. Summary of SEG-REWET heat-treatment application and samples

Objective	Mimic predicted dry storage system peak clad temperatures representative of the dry storage system fleet followed by quench (effects of being in dry storage and then placed back into a pool for fuel transfer). Fuel rod segments will be held at temperature, allowed to relatively slowly cool to an intermediate temperature, and then quenched in water (hold times and temperatures to be determined). Some of the quenched segments will also be reheated to simulate a secondary drying process that would be performed when the fuel is repackaged.
Initial conditions	Punctured, segmented, fueled
Sample size	As specified by the individual DE to be performed, 1 to 6 in.; see cutting plan. Longer segments may be utilized for the heat treatment and cut a second time to achieve a more economic heat-treatment cycle.
Samples	Initially six segments from 1 M5 and 1 Zirlo T0 rod (may be expanded or eliminated based on initial segment test results) (6U3M09,30AG09)
Reserved backup samples	Available from the three backup T0 rods.
Information or benefit obtained	The T1 condition will not be available from RPC rods because the cask rods will not be destructively examined at T1; thus the SEG, SEG-REWET, and FHT rods must provide the sum of information on the separate effects related to the peak thermal cycling. This test is designed to provide information to address the fuel transfer options gap. Incremental comparisons will be made on heat-treated segments, heat-treated then cooled then rewet segments, and heat-treated, then cooled, then rewet, then heat-treated again to evaluate if the thermal cycling affects the characteristics of the cladding and composite fuel properties.
Prerequisites	NDE and sample prep, excluding heat treatment; end cap welding and pressurization; validate segmented heat-treatment approach based on data from FHT samples.

3.3.2 ROUGH SEGMENTING

An initial plan for segmenting the sister rods is provided in Appendix A. The cutting plans will be used to guide the early planning efforts. The preliminary cutting plan specifies the location of the desired specimens and the associated examinations (e.g., metallographic/scanning electron microscope [MET/SEM] mount, mechanical test specimen, hydrogen analysis). Once the NDE data have been obtained, the cutting plans will be revised.

ORNL's ADEPT equipment (Figure 3) will be used to segment the rods for the various DEs (see Section 3.4). The initial ADEPT segment cuts are considered "rough"; the specimen preparation required for most other DEs will be conducted as a part of that DE and allocated segments may be further segmented (using ADEPT or other means) to achieve the necessary specimen dimensions for the DE. The requirements of each DE (specimen size, number of specimens, specimen conditions desired [e.g., fueled/defueled]) are provided with the DE description.

As rough cuts are completed, fuel segments will be mechanically marked to indicate the top of the segment, and, for traceability and to prevent contamination, each segment will be placed into a container marked with the segment ID (see Section 3.1 for nomenclature) as illustrated in Figure 4. Although the containers are not considered to be leak tight, they are generally sufficient to eliminate ingress of liquids and solids. Containerized segments will be stored with other segments destined for the same DE until the facilities are ready to receive them. Segments to be examined at laboratories other than ORNL will be marked and packaged in the same way and will then be placed into shielded storage until enough segments are collected to warrant a shipment.

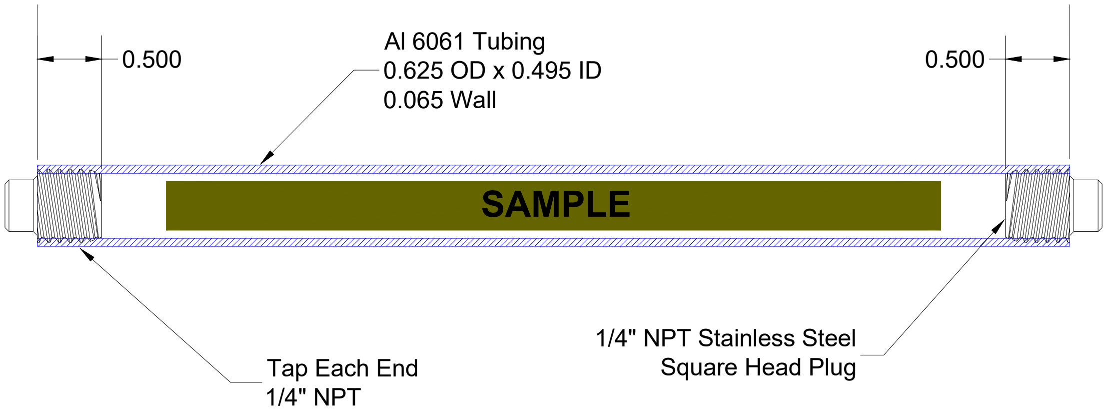


Figure 4 Example segment container configuration.

3.3.3 DEFUELING

Many of the DEs require only the cladding; therefore, the fuel must be removed from those segments without damaging the clad. Most of the defueling will be accomplished by soaking the segments in nitric acid, as illustrated by Figure 5, and then rinsing to remove residual contaminants on the clad surface providing for a clean surface and lower dose rates.

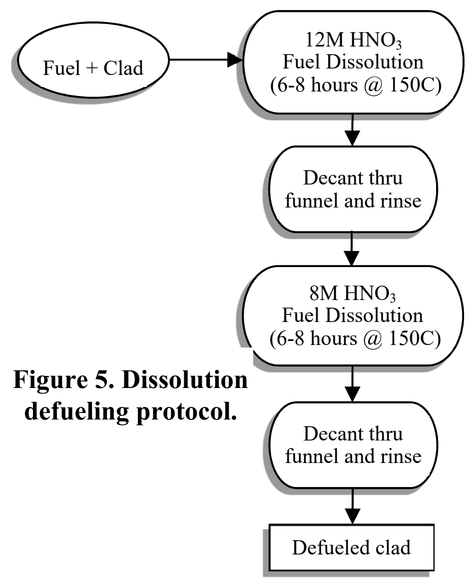


Figure 5. Dissolution defueling protocol.

Zircaloy-based cladding is impervious to nitric acid and therefore will not be damaged during the hot acid defueling. The defueled clad will be routed to the appropriate laboratory for further sample preparation followed by DE. Some segments may be partially defueled by mechanical means prior to chemical defueling

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3.4 PHASE II: DESTRUCTIVE EXAMINATIONS

Table 7 describes and prioritizes the nominal planned DE. Section 3.4.1 discusses the approach used to select test sample sizes and particular specimens, with a summary test matrix provided in Table 8. The number of samples per DE is expected to evolve as information from the testing becomes available.

Prior to beginning the DE, sister rod specimens must be prepared as described in Section 3.3. The sister rods will be segmented per detailed cutting diagrams and in accordance with the specifications for the DE. The preliminary cutting diagrams in Appendix A will be reconsidered as the results of the NDE allow for identification and location of landmarks such as pellet/pellet interfaces, the burnup gradients, and wear marks due to in-reactor interface with the grid spacers prior to segmenting. DE will begin after acceptance of the NDE results and development of the final cutting plan for each rod on a rod-by-rod basis. ANL will be provided with defueled cladding segments to support ring compression testing (see Section 3.4.2).

Not all examinations will be performed on all rods. The sections following Table 8 summarize each DE, including the number of specimens per test.

Table 7. Nominal destructive examinations

Exam No.	Examination / Operation	Examination objective (primary goal in italics)	Related technical gaps [2]	Priority
DE.01	Puncture, rod internal pressure measurement, gas analysis, and free volume estimation	*Rod internal pressure, fission gas volume and composition*	Stress profiles, cladding creep, cladding H_2 effects: hydride reorientation and embrittlement	1
DE.02	Metallographic / hydrogen / optical examinations	*Cladding: Hydride structure, oxide thickness, grain size analysis, hydride distribution and orientation, and hydride rim thickness* *Fuel: radial profile, grain structure, porosity, bond with cladding*	Cladding H_2 effects: hydride reorientation and embrittlement, cladding oxidation; pellet high-burnup (HBU) rim and pellet respirable fractions	2
DE.03	Clad hydrogen analysis (total H_2)	*Validate and quantify the optical total hydride content* observations (limited samples)	Total hydrogen content of clad at HBU	3
DE.04	Spiral notch toughness test	*Fracture toughness*, interface bonding efficiency Also, shear resistance/ modulus; ductile-to-brittle transition temperature (*DBTT) in phase III*	Embrittlement, stress profiles	4
DE.05	Cyclic integrated reversible bending fatigue test (CIRFT) *Dynamic* *Static* *Cumulative effects*	*Fatigue life* (dynamic) Mechanical properties (static) *Cumulative impact effect on fatigue life* (dynamic) Also, Young's modulus, fatigue strength, S-N curve, flexural strength, interface bonding efficiency, ultimate tensile strength*, collection of fuel aerosolized particulates that are released on rupture*	Characterize the cumulative effects of extended vibration and the cumulative effects of low g normal condition impacts (rod-to-rod or rod-to-basket). Stress profiles, fuel fragmentation/small particles and aerosols. Also cladding thermal fatigue.	5
DE.06	Scanning electron microscope examination of fuel and cladding	*Microstructure, hydride structure, Oxide thickness, grain size analysis, fuel radial profile, clad thickness*; as needed to validate other observations	Supports the characterization of the cumulative effects of extended vibration, stress Profiles, fuel fragmentation magnitude	6
DE.07	Four-point bending test	With and without fuel to obtain *flexural modulus, flexural stress, flexural strain* using traditional testing methods. Further validate CIRFT methods; allow for direct data comparison with other measurements and future measurements	Stress profiles, fuel fragmentation—small particles/aerosols	7
DE.08	Tube tensile/axial testing of fuel cladding	*Axial yield strength, ultimate tensile strength, uniform elongation, total elongation; calculate Young's Modulus, Poisson's ratio. Strain hardening*	Stress profiles, cladding creep, cladding H_2 effects: hydride reorientation and embrittlement	8
DE.09	Microhardness (µH)	*Closely correlated to the material's tensile properties and used as a substitute where additional large samples are not available*	Stress profiles	9
DE.10	Ring compression tests (RCT) (fueled and unfueled)	*Stress/strain relationship; DBTT when applied as a function of temperature*. On fueled samples *stress/strain relationship. Compare fueled and unfueled results*	Stress profiles, cladding creep, cladding H_2 Effects: Hydride Reorientation and Embrittlement	10
DE.11	Expanded cone-wedge testing (ECW)	*Hoop stress/strain. Young's modulus, yield and ultimate stress, uniform elongation, strain hardening behavior*	Hoop stress capability of spent nuclear fuel clad	11
DE.12	Emissivity (ε)	*Waterside surface emissivity for heat transfer calculations*	Stress profiles, cladding creep, cladding H_2 effects: hydride reorientation and embrittlement	12
DE.13	Cladding and fuel/clad interface TEM	*Microstructure: hydride type/alignment, general defect microstructure, radiation-induced segregation.* Performed as needed to validate the underlying microstructure inherent in mechanical testing observations	Supports the characterization of the stress profiles and performance of the fuel system during storage and transport	13

Table 8. Number of samples per destructive examination type for Phase II testing

			DE # tests/applicable notes												
Rod	**Alloy**	**Application**	**DE.01 puncture**	**DE.02[e] MET/H_2**	**DE.03 Total H_2**	**DE.04 SNTT**	**DE.05 CIRFT**	**DE.06 SEM**	**DE.07 4PB**	**DE.08 AxTen**	**DE.09 µH**	**DE.10[e] RCT**	**DE.11 ECW**	**DE.12 ε**	**DE.13 TEM**
6U3I07	Zirlo	Baseline and T1	1	3/a 1/b,SEG	3/a,j 1/b,SEG,j	2/c 1/b,SEG	dynamic 2/a dynamic 2/a/k/SEG static 1/c cumulative 1/c	0/g	2/a 1/b, SEG	2/c 1/b,SEG	4/a	4/a,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3D8E14	Zirlo	Baseline and T1	1	5/a 3/b,SEG-REWET	5/a,j 3/b,SEG-REWET,j	3/c	dynamic 3/a static 1/c cumulative 1/c	4/g	3/a 3/b, SEG-REWET	3/c	4/a	3/a,f,j,SEG 1/d 1/d,j 1/b,j,SEG-REWET	3/d,j	0	1/g
3D8B02	Zirlo	Baseline and T1	1	4/a	4/a,j	3/c	Dynamic 3/a static 1/c cumulative 1/c	4/g	3/a	3/c	4/a	4/a,f,j,SEG 1/d 1/d,j	3/d,j	0	1/g
30AD05	M5	Baseline and T1	1	5/a 3/b,SEG-REWET	5/a,j 3/b,SEG-REWET,j	3/c	dynamic 1/a dynamic 2/a/k/SEG static 1/c cumulative 1/c	4/g	3/a 3/b, SEG-REWET	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j 1/b,j,SEG-REWET	3/d,j	0	1/g
30AE14	M5	Baseline and T1	1	6/a	6/a	3/c	Dynamic 1/a static 1/c cumulative 1/c	4/g	3/a	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j	3/d,j	0	1/g
5K7O14	M5	Baseline and T1	1	6/a	6/a	3/c	Dynamic 1/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3A1B16	low-tin Zirc-4	Baseline and T1	1	5/a	5/a	3/c	Dynamic 1/a dynamic 2/a/k/SEG static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	1/b,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3F9D07	Zirlo	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0
3A1F05	low-tin Zirc-4	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0
30AK09	M5	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 8. Number of samples per destructive examination type for Phase II testing (continued)

			DE # tests/applicable notes												
Rod	**Alloy**	**Application**	**DE.01 puncture**	**DE.02[e] MET/H_2**	**DE.03 Total H_2**	**DE.04 SNTT**	**DE.05 CIRFT**	**DE.06 SEM**	**DE.07 4PB**	**DE.08 AxTen**	**DE.09 µH**	**DE.10[h] RCT**	**DE.11 ECW**	**DE.12 ε**	**DE.13 TEM**
F35P17	Zirc-4	T1 rod	1 following FHT	4/a	4/a,j	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	1/b,f,j,FHT 1/b,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0/g
6U3MO9	Zirlo	T1 rod	1 following FHT	4/a	4/a,j	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/b,f,j,FHT 2/a,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0/g
30AG09	M5	T1 rod	1 following FHT	5/a	5/a,j	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/a,f,j,FHT 1/a,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0
6U3K09	Zirlo	T1 backup rod	1 after primary T1 DE	0	0	0	0	0	0	0	0	0	0	0	0
3F9N05	Zirlo	T1 backup rod	1 after primary T1 DE	0	0	0	0	0	0	0	0	0	0	0	0
Specimen size required (in.)				0.5	Included in DE.02 material allocated	4	6	N/A	6	6	Included in DE.02	3.5 with some portion used for METs/H_2	0.5	Dedicated sample not needed	N/A
				Initially Anticipated Material Allocations											
Total length used, SEG/SEG-REWET (in.)			**166.0**	3.5	N/A	4.0	30	N/A	42.0	6.0	0	80.5	0	0	N/A
Total length used, FHT (in.)			**289.0**	6.5	N/A	36.0	90.0	N/A	54.0	54.0	<2.0	42.0	4.5	0	N/A
Total length used, T0 (in.)			**558.5**	17.0	N/A	80.0	162.0	N/A	120.0	120.0	0	49.0	10.5	0	N/A
Defueled Length required(in.)			**165.0**	0	13.5	0	0	N/A	0	0	0	136.5	15.0	0	N/A
***Total length used* (in.)**			**1011.5**	27.0	N/A	120.0	282.0	N/A	216.0	180.0	0	171.5	15.0	0	N/A
Total number of samples			**393**	54	54	30	47	16	36	30	40	49	30	3	4

NOTES:

[a] Samples taken from locations spaced along the rod in Zones 1, 2, and 3, with one sample from Zone 4.
[b] Samples taken from Zone 1
[c] Samples taken from Zone 1 and Zone 2.
[d] Samples taken from Zone 1, 2 and 3.
[e] ANL DE.10 includes material allocated for one pre-test DE.02, one post-test DE.02, and one DE.03 measurement and the total length of material used is tabulated under DE.10.
[f] ANL DE.10 four test specimens are derived from each 3.5 in. segment allocated.
[g] As required based on the results of other DE.
[h] Four RCT test specimens are derived from each segment allocated.
[j] defueled specimen.
[k] a pair of specimens that will be thermally cycled (~10x) prior to the test, one pressurized and one depressurized

3.4.1 DE SAMPLE SELECTION APPROACH

One of the primary objectives of the sister rod selection process was to acquire rods with a wide range of characteristics such that the attributes that result in reducing rod strength and ductility could be identified after detailed examination. For this project, all of the fuel rods were manufactured to about the same enrichment and were operated to about the same EOL burnup. Generally, from a bird's-eye view, the sister rods and their RPC partners in dry storage are considered to be some 8,500 rods from the same population—that is, rods composed of zirconium-based alloy cladding and UO_2 fuel pellets operated in a commercial pressurized water reactor (PWR) starting with similar ^{235}U enrichments and ending with similar burnups.

It is well known that the final SNF rod condition is path-dependent and that rods having the same initial enrichment and final burnup may not have been subjected to the same duty in the reactor. Thus, to draw conclusions or construct empirical relationships for the population of HBU rods, it is important to characterize the final configuration of the as-received sister rods and to understand their operating history.

Within the mechanical DE, it is particularly important to describe the populations of interest and to draw an appropriate number of samples to support the objectives of the program. Too many samples may waste time, resources and money; while too few may lead to incorrect conclusions about the SNF performance. Given the limited amount of materials available, it is clear that samples must be judiciously selected to obtain sufficient applicable data to draw meaningful conclusions. Therefore, the material-based, design/geometry-based, and operationally-based characteristics of the sister rods as discussed in the following sections are considered for purposes of selecting an appropriate number of samples and characterizing the test data that are obtained. Additionally, the test type and data applications themselves are discussed as related to sample size selection. The following segment sizes are required for the various examinations:

- DE.01 (puncture), not applicable;
- Optical examinations (DE.02, DE.06 and DE.13), < 0.5 in.;
- DE.03, DE.09, very small sample taken from other samples;
- DE.04, 4 in. fuel in cladding;
- DE.05, DE.07, DE.08, 6 in. fueled cladding;
- DE.10, 3.5 in. fueled/defueled cladding to be subsectioned providing four RCT specimens and including companion specimens for pre-test and post-test optical and total hydrogen measurements;
- DE.11, 0.5 in. fueled; and
- DE.12, specimens taken from previous tests.

3.4.1.1 MATERIAL-BASED POPULATIONS

Of the 25 fuel rods selected as sister rods, 15 will be retained by ORNL for DE. Four cladding materials are represented: M5 (five rods), Zirlo (seven rods), Zirc-4 (one rod), and low-tin Zirc-4 (two rods). No IFBA rods are included. Although several of the rods came from the same assembly production batches, there is no evidence that the cladding used came from the same production lots. Thus, similarity for the rod cladding is based upon the fuel vendor's specification and acceptance criteria for the material.

All rods are fueled with UO_2 pellets with similar enrichments. Like the fuel cladding, although several assemblies were manufactured in the same production batch, there is no evidence that the pellets came from the same production lots. Therefore, similarity for the fuel pellets must rely upon the fuel vendor's specification and acceptance criteria.

3.4.1.2 DESIGN AND GEOMETRY-BASED POPULATIONS

All of the Zirlo rods are the Westinghouse North Anna Improved Fuel (NAIF/P+Z) design; the M5 rods are AREVA's Advanced Mark-BW design (AMBW); the Zirc-4 rod is the Westinghouse low parasitic (LOPAR) fuel assembly design; and the low tin Zirc-4 rods are the Westinghouse NAIF fuel assembly design. Thus, ten are Westinghouse-designed and manufactured and five are AREVA-designed and manufactured.

The AREVA M5 rods were manufactured in two different production batches. The Zirlo rods were manufactured in three different production batches. Both low-tin Zirc-4 rods came from the same manufacturing batch.

3.4.1.3 OPERATIONALLY-RELATED POPULATIONS

All sister rods have an average burnup greater than 45 GWd/MTU. Given the very small variations in beginning-of-life (BOL) enrichment from rod to rod, and the relatively small variations in EOL burnup, the ORNL sister rods as a collection are generally considered to be 15 samples from the same population of burnup and enrichment. However, the reactors were uprated twice. Some of the sister rod donor assemblies (F35, 30A) were operated during uprate cycles. F35 was operated early in the life of the reactor and over its lifetime had a lower average linear heat rate during operation than other sister rod donor assemblies. 30A was operated at the reactor's highest rated power and linear heat rate.

The location within the fuel assembly lattice influences the irradiation environment. Although most of the sister rods were operated in different lattice positions, the assembly lattice positions themselves can be generically classified as corner rods, peripheral rods, rods adjacent to guide tubes, and typical rods, as illustrated in Figure 6. Using this more generic classification definition, the ORNL sister rods include: seven rods that had a single face adjacent to a guide tube cell; four rods that had a face and a corner-adjacent to a guide tube cell; two rods that were operated in fuel-rod-only cells; one rod that was single-corner adjacent to a guide tube cell (considered a typical cell based on grid spring/dimple interfaces but experienced effects from the guide tube cell); and one rod that was a peripheral rod (next to a corner location). The two rods labeled as "fuel rod cells" all came from corner-adjacent positions.

The rod internal pressure (RIP) of the ORNL sister rods is expected to vary between 2.8 and 5.8 MPa at room temperature (293K); based on the initial rod fill pressures, rods from F35 are expected to have the highest EOL RIP. Zirlo rods, namely sister rods from 6U3 and 3F9, are expected to have relatively high RIP. M5 sister rod RIPs are expected to be in the middle of the range. Hydrogen pickup is strongly related to cladding oxidation rates, which are related to residence time in reactor and local temperatures. Since residence time and temperature are strongly related to fuel burnup, oxidation and hydrogen pickup are often correlated with burnup. Zirlo, Zirc-4, and low-tin Zirc-4 are expected to have much higher total cladding hydrogen content than M5-clad rods. Estimates of RIP and cladding hydrogen content are used to select sister rods for FHT.

As of January 2017, the range of cooling times for the 15 ORNL sister rods is 6 to 22 years; the average cooling time is 12 years. On average, the rod decay heat is approximately 3.5 W for the sister rods (excluding the two from assembly F35). The predicted axial burnup profiles for the fuel assemblies are expected to be generally similar to the axial profile shown in in Figure 6 [13]. Since the axial decay heat profile generally follows the burnup profile, the decay heat as a function of elevation is considered to be consistent among the rods, as scaled by the rod's predicted decay heat.

Because each rod's burnup (and therefore decay heat) varies axially along the rod, the sister rods can each be segregated further into zones based on burnup and decay heat measurements or predictions. Per Figure 6, the burnup decay heat axial profile is fairly flat over most of the active fuel region; roughly 75% of central rod region is at the same burnup/decay heat value (typically 110% of the rod average value). The bottom and top ~12% of the active fuel region has a steep burnup gradient, where the exposure drops from the central rod region value to about 75% of the rod average burnup in essentially a linear fashion. The exposure/decay heat generation drops about 7% at spacer grid locations [13], putting those elevations into a separate population. Finally, the cladding in the non-fueled regions of the rods has much lower fluence than the cladding in the active fuel region, and thus must be treated as a separate population.

Axial temperature variations are also expected to occur within the RPC; the hotter areas are located in the central and upper elevations of the RPC. Any effects of temperature variation should be imposed on the FHT heat-treated rods and observed on the cask rods (at T10).

Given these axial variations, the rod populations for Phase II are generally zoned for purposes of sample selection and description as illustrated in Figure 6. The amount of material available for DE in Phase II (10 rods, including 3 sister rods that are allocated to FHT) is estimated as:

Zone 1: HBU, hottest, fueled elevations; 740 in.
Zone 2: HBU, fueled elevations; 200 in.
Zone 3: variable lower burnup, fueled elevations; 400 in.
Zone 4: under-grid fueled elevations; 120 in.
Zone 5: unfueled elevations; 60 in.

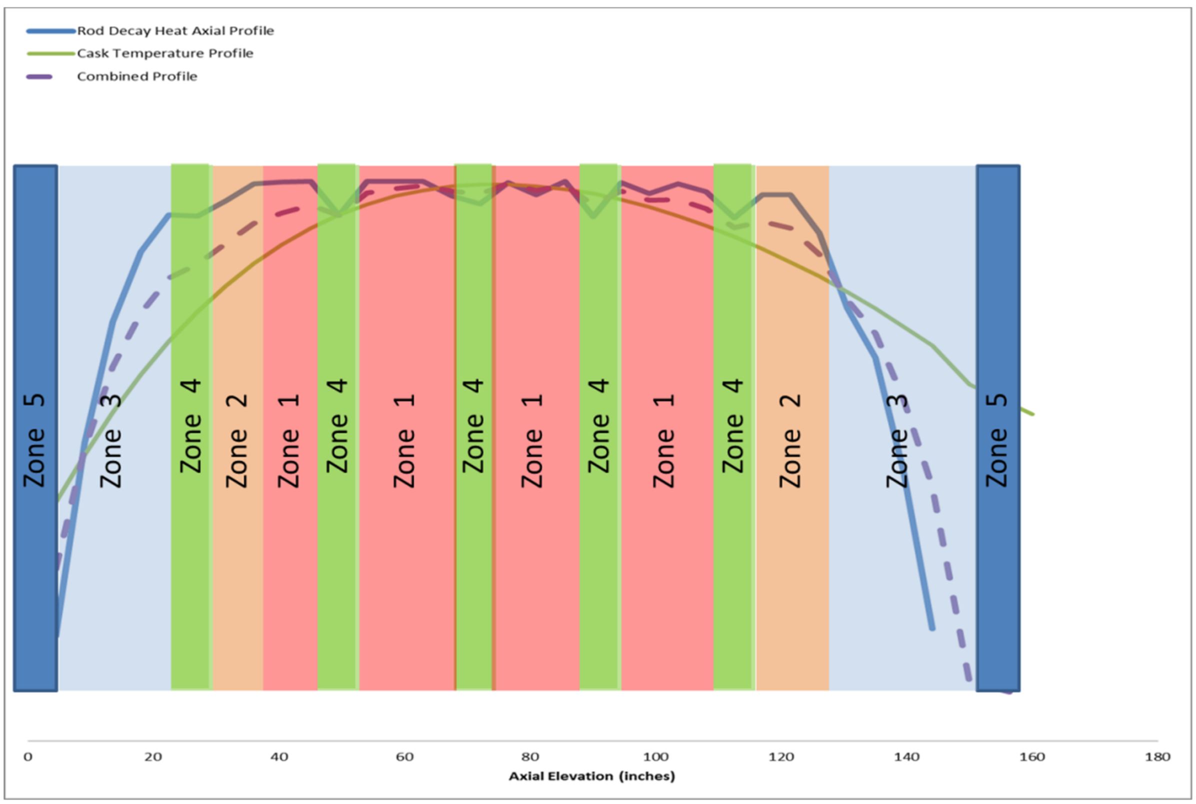


Figure 6. Predicted axial burnup profile and sample zoning approach for the RPC assemblies and inferred for the sister rods.

3.4.1.4 TEST TYPE AND DATA APPLICATION CATEGORIES

Each of the Phase II mechanical tests can be categorized by loading/event rate, temperature range, data type, and quantity of previous data available. This information, summarized in Table 9, can be used to further guide the number of samples allocated per test.

Table 9. Mechanical test type and data application categories

Test	Sample test loading type	Temperature of sample during Phase II test	Data application type	Quantity of data available for decision-making (not necessarily irradiated or high burnup)*
DE.04 SNTT	Dynamic	Ambient	Inferential, quantitative	None on SNF
DE.05 CIRFT	Dynamic	Ambient	Inferential, qualitative, and quantitative	72 data points (4 alloys) [20]
DE.07 four-point bending	Quasi-Static	Ambient	Quantitative	>17 (unirradiated and irradiated, defueled Studsvick, JAEA,ANL) [22,23]
DE.08 Axial tension	Quasi-Static	Ambient	Quantitative	Many, mainly tube machined dogbone specimens [26]
DE.09 Microhardness	Quasi-Static	Ambient	Inferential, qualitative, and quantitative	A few studies available each with several data points [19,24]
DE.10 RCT	Dynamic and quasi-static	90 to 150°C	Inferential, qualitative, quantitative	>67 data points (3 alloys, ANL [21]) Several other non-US studies have been published
DE.11 Expanded cone-wedge	Quasi-static	Ambient	Quantitative	10 data points (ORNL [25]) Several other data points using variants of this test are available

*Note that an exhaustive literature review has not be performed.

The mechanical tests being performed fall into two categories with respect to the loading rate: quasi-static and dynamic. Dynamic testing typically results in more data scatter because of the greater number of uncertainties inherent in the event (crack propagation, for example) and the data capture rate of the instrumentation. By contrast, quasi-static test events (yield, for example) are slower, are usually section average events, and are easier to capture with accuracy and repeatability. Therefore, dynamic testing usually requires more data points to substantiate a trend at a particular confidence level.

Determination of the specimen characteristics as a function of temperature requires that specimens be provided for each temperature to be tested. During Phase II, only DE.09 (defueled) tests will be temperature-dependent. To accommodate this, each DE.09 rough-cut sample has been allocated sufficient material for four subsamples, accommodating four variations on test temperature.

Data from the testing can be used in several ways:

(1) descriptively to characterize the main features of the HBU performance,
(2) investigatively to discover previously unknown behavior,
(3) inferentially to test the current theories on the behavior,
(4) qualitatively to find out what happens to one variable as another is changed, and
(5) quantitatively to constructing empirical relationships for the purpose of mechanistically modeling and predicting the specific relationship between variables.

The requirement for a larger quantity of data and for more specific data is increased as testing progresses from 1 to 5. Although the combined data provided by the tests will be applied in all five areas, a primary objective of the tests is to quantify the mechanical material properties to allow modeling and prediction of a specimen's performance during storage and transport (item 5). Additionally, a primary objective is to confirm or reject the postulated impact of storage temperatures and environmental conditions (namely hydride reorientation and vibration effects) on the fuel's performance during storage and transport (item 3).

3.4.1.5 COMPARITIVE SPECIMENS

In addition to allowing for the variations in the material itself (material, design, operation) and the types of tests and data applications, for separate effects testing it is also important that specimens be paired as closely as possible to allow for more relevant comparisons.

Specimen pairing within single sister rods is used for 4PB, CIRFT, and RCT. 4PB tests will be used to examine the response to T1 conditions (SEG-REWET) as compared with the baseline and for this purpose contiguous 4PB specimens are allocated from a single rod in Zone 1 to reduce the potential for variation and for direct observation of the separate effects. To provide as much local data as possible to support direct conclusions from the 4PB data, DE.02 and DE.03 (MET/H_2 and total hydrogen, respectively) samples are also paired with the 4PB specimens. CIRFT includes static, dynamic, and cumulative effects tests and contiguous and/or near specimens are used as much as possible to improve comparability. Several heat treatments are proposed for RCT both at ORNL and at ANL; therefore, paired ORNL/ANL specimens are provided, both for improved separate effects comparisons and for cross-laboratory comparisons.

Paired specimens are also used from sister rod-to-sister rod primarily to compare the various cladding types for SNTT, CIRFT, 4PB, AxTen, and RCT. For example, to allow for a direct comparison of the results of mechanical tests such as SNTT between cladding types, Zone 1 specimens at similar elevations are specified for each sister rod. Paired samples are specified in this manner throughout the test matrix to improve comparability among specimens. Adjustments may be required pending the results of the NDE and local sister rod burnup evaluations. µH and ECW require much smaller samples and are specified opportunistically where the material is expected to be available; adjustments and/or additional specimens may be selected based on the NDE and additional material availability following other DE. Information about the local cladding and pellet conditions for these tests primarily relies on the periodic DE.02 and DE.03 samples.

Additionally, as mentioned previously, the burnup along each sister rod varies axially and includes burnup depressions at grid locations (including mixing grids). Grid locations may also include wear marks on the cladding due to grid-to-rod fretting (GTRF) in reactor, and these marks may act as stress risers, potentially reducing the load bearing capability of the composite rod and cladding. To encompass the effects of burnup variations and to test the full range of burnups available within the sister rods, rod-to-rod paired specimens from Zone 2, 3 and 4 are also specified; unfueled regions (Zone 5) are not currently specified for this purpose. Specimens expected to have wear marks are specifically paired with other worn specimens with the GTRF marks centered, as possible, on the rough-cut segment. CRUD likely indicates areas of thicker oxidation and higher cladding hydrogen content, and those locations may be reallocated to specific tests as indicated by the NDE.

It is further expected that cask rod specimens (T10) will be paired with the sister rod specimens for direct comparison after the dry storage demonstration period. Paired rods are listed in Table 1 and Table 2, and corresponding examinations and specimens are expected to be selected based on the completed sister rod examinations and using the cask rod NDE as guidance (planned for FY2026 and to be discussed in future test plan documents).

3.4.1.6 SUMMARY OF TEST POPULATIONS AND DISTRIBUTION OF MATERIAL

A minimal sample selection has been specified to efficiently characterize the populations described in Sections 3.4.1.1 through 3.4.1.5. The distribution of material has been selected primarily based on cladding alloy, axial zones, the heat treatment to be applied, and pairing of specimens for separate effects comparisons. Where it may be possible to reach conclusions based on results from an initial data set (i.e., for inferential applications such as SEG, SEG-REWET), a smaller number of test samples has been allocated as a starting point, with material reserved for additional studies if results warrant further testing. Given the minimalistic approach and very limited amount of material available, dynamic tests have been allocated approximately the same number of specimens as the static tests. That approach is not ideal; however, it may be possible to allocate additional material to the dynamic tests after the initial mechanical tests are completed. Also, due to the minimalistic approach and material limitations, higher-priority DEs (see Table 7) are assigned approximately the same amount of material as lower-priority DEs. The FHT heat-treated rods are assigned in the same manner; the SEG and SEG-REWET samples are taken from the baseline rods; most of the SEG material is used for ANL RCT. Table 8 provides a summary of the material allocated for the various ORNL and ANL tests.

Each Zone 4 region is necessarily short (grid heights on the order of 2 in.). Samples intending to specifically test performance in the grid region may therefore extend into the regions on each side of the Zone 4 region. The cutting diagrams provided in Appendix A show the axial elevations of the allocated samples.

Because a limited amount of material is available and a statistically based method for allocating the material cannot be used, the data observed from each test will be monitored to determine if a test can be concluded earlier based on the confidence level achieved as the work progresses. If a test can be concluded early, the material can be reallocated to other tests as necessary. Section 3.4.1.7 discusses the proposed stopping criteria.

3.4.1.7 STOPPING CRITERIA

An objective of the sister rod test program is to determine the mean attributes (e.g., fatigue life, tensile strength, fracture toughness) of the sister rod populations of interest with a high enough confidence level to allow inferences and conclusions based on the measurements. Typically, several measurements are made for each load level from a pool of like specimens to determine a mean and standard deviation for the population. In the case of the sister rods, many subpopulations within the pool of material (e.g., alloy, operational) are expected. However, it is possible that the subpopulations identified have little effect on the results of the experiments; that is, as an example, it is possible that the results for M5 and Zirlo will be the same for certain tests at T0.

To ensure the best use of the material in hand, an approach to evaluating the existing data with the additional data provided by each test will be used. Bayesian (highest-density interval region of practical equivalence) or equivalent statistics-based methods will be used to continuously evaluate the state of the knowledge base regarding each data set, and will be updated as additional data are received. As the data supports or refutes the proposed theories and/or empirical models, the number of allocated samples will be revised. Also, tests may be discontinued as enough inferential test results are obtained to make a conclusion, and the untested samples may be allocated to other tests.

3.4.2 DESTRUCTIVE EXAMINATIONS

All specimens used in the mechanical testing will be characterized for hydride content and orientation via optical methods (DE.02) and/or through hot vacuum testing (DE.03). Where practical, the hydride content and orientation may be inferred through results from nearby samples. When indicated by the test results, additional post-test fractographic or other optical examinations (DE.06 and DE.13) may be performed to characterize failure regions or other regions of interest.

3.4.2.1 DE.01 FISSION GAS PUNCTURE, PRESSURE MEASUREMENT, GAS ANALYSIS, AND FREE VOLUME ESTIMATION

Table 10 summarizes the DE.01 examinations. The ADEPT equipment will be used for the rod puncture. The rod pressure and plenum volume measurement relies on the ideal gas law as a basis and assumes constant temperature operation; a reference volume is used as the standard, and the change in pressures as volumes are valved in and out are used to compute the values of interest. The measurement uncertainty is directly related to the volume of the test fixture. A new apparatus has been proposed for the ADEPT apparatus that improves performance and provides for longer life and better selection of components. The conceptual design, shown in Figure 7, has an estimated uncertainty of 5%.

The puncture apparatus interface must be configured for the rod diameter and end plug length to provide a good seal and to minimize fixture volume. Some rods may require more than one puncture, although past experience and studies indicate that there is good communication between the fuel column region and the plenum. Pressure as a function of time will be measured. Detailed drawings of the rod plenum regions will be needed to design and fabricate this equipment.

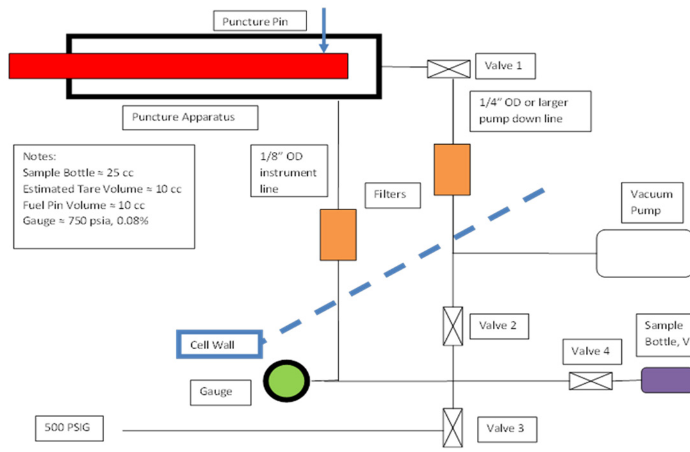


Figure 7. Rod Pressure and Free Volume Equipment Set Up

Table 10. DE.01 gas puncture summary

Objective	The EOL RIP, total moles of gas present, fission gas constituents, and fuel rod free volume will be measured. The fission gas sample will be analyzed for the major fission gas isotopes (e.g., Kr and Xe). The sample will also be examined for unexpected gases.
Initial conditions	Unpunctured, fueled; most are to be punctured in the plenum region, but at least one rod will be punctured in other axial locations to assess axial communicability of the fission gas, as possible.
Sample size	Full rod
Total number of samples	15, with up to 5 rods punctured after FHT. Also, 10 T0 PNNL rods to be punctured prior to shipment.
Information or benefit obtained	RIP, free volume, and fission gas composition; gas pressure to be monitored as a function of time during the puncture.
Prerequisites	NDE.01 through .06; FHT full rod heat treatments (nominally 3 of the 15 rods to be punctured with 2 backup FHT rods reserved).

3.4.2.2 DE.02: METALLOGRAPHIC AND HYDRIDE EXAMINATION OF FUEL AND CLADDING

Table 11 provides a summary of the metallographic and hydrogen (MET/H_2) mounts. METs will be prepared, polished, and optically photographed. The mounts may also be etched to provide better resolution of the grain structure and to allow analysis of the grain size. Typical images are shown in Figure 8 and Figure 9.

Table 11. DE.02 MET/H_2 summary

Objective	Characterize general condition of the fuel system: measure clad oxide layer thickness (external and internal), fuel/clad interactions, fuel restructuring, rim effects, and agglomerate behavior. Characterize the orientation and quantity of hydrides present in the cladding.
Initial conditions	Segment for planned MET/H_2 specimen (see Appendix A cutting plans), rough cut, mounted, polished or selected from mechanical testing specimen following fracture to provide additional information.
Sample size	< 0.5 in.
Number of samples	108 (54 at ORNL, 54 at ANL)
Information or benefit obtained	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

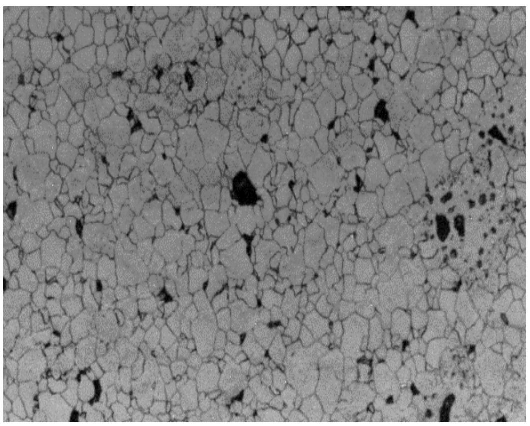


Figure 8. An example of a MET/ H_2 mount after etching showing the grain boundary enhancement.

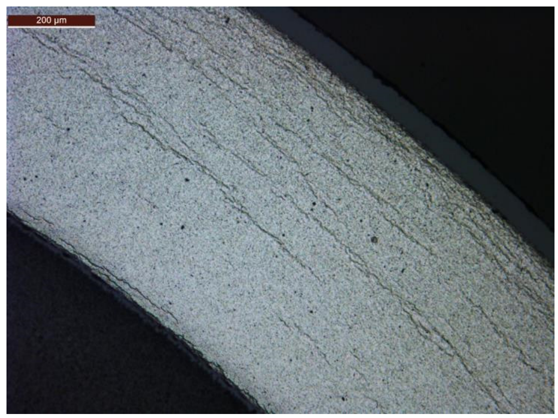


Figure 9. A lower magnification MET/ H_2 mount example showing the hydride morphology of a cladding section.

3.4.2.3 DE.03: CLAD HYDROGEN ANALYSIS

The clad hydrogen content will be determined by the inert gas fusion process such as that employed by the LECO-type units. Small samples (~ 100 mg) are heated in the analyzer, and the hydrides in the clad are vaporized and released into the analyzer's inert carrier gas. The hydrogen content in the carrier gas is determined based on thermal conductivity measurements of the gas. The uncertainty of the measurement is estimated as ±10% (µg H/g metal). Table 12 summarizes the DE.03 measurements.

Selected ~6 mm long defueled specimens will be analyzed by subsectioning in both the longitudinal and azimuthal directions. The hydrogen concentration will be calibrated to the metal mass, considering the oxide layer thickness determined in DE.02. Further, the hydrogen content of many specimens will be determined after mechanical testing (e.g., tensile, burst, creep) to further verify correlations between hydrides and structural performance used in simulation models.

Table 12. DE.03 total H_2 summary

Objective	Characterize the total quantity of hydrides present in the cladding.
Initial conditions	Defueled segments. A very small amount of material is needed and will be taken from selected mechanical test samples.
Sample size	<< 0.5 inch
Number of samples	81 (54 samples at ORNL, 27 at ANL)
Information or benefit obtained	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

3.4.2.4 DE.04: SPIRAL NOTCH TOUGHNESS TESTING

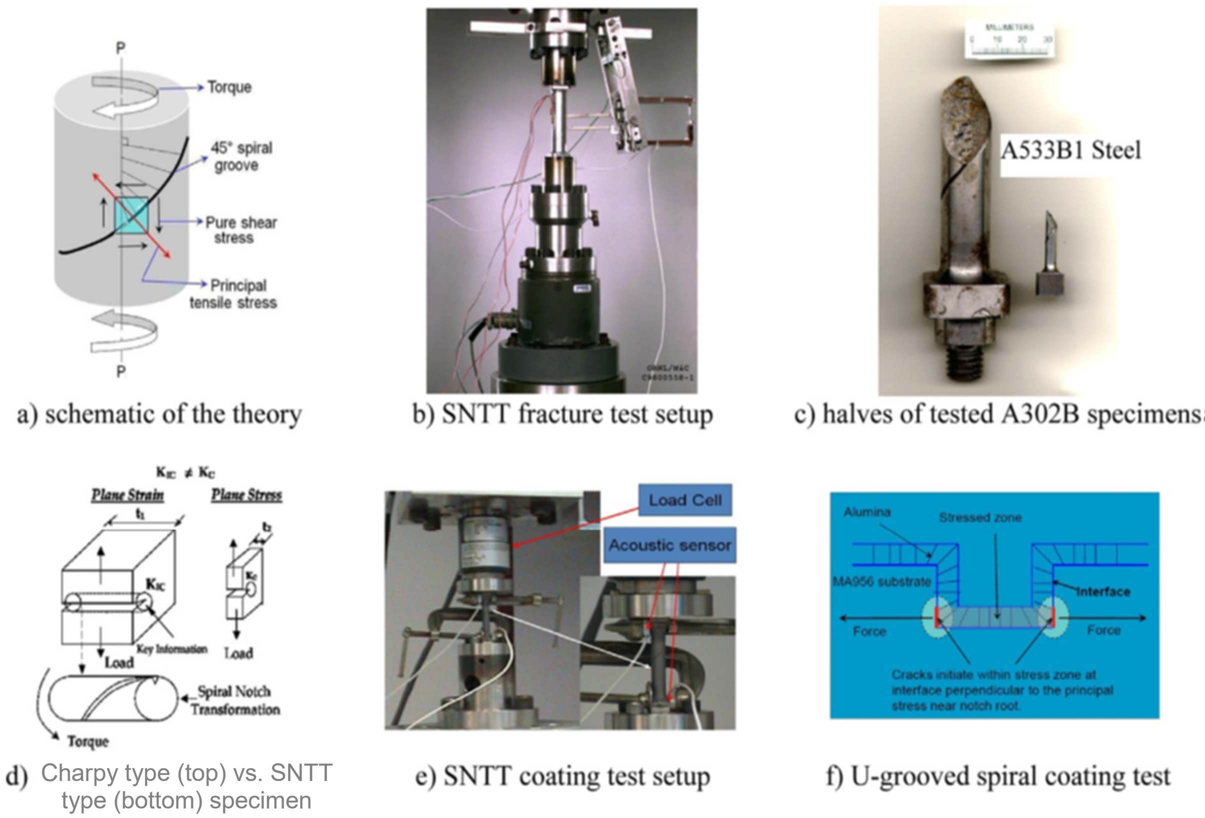
Table 13 summarizes the DE.04 testing to be completed. The spiral notch toughness test (SNTT) applies load in torsion to measure the fundamental shear properties and to evaluate the fracture toughness of the composite fuel rod. The torsion test is a technique for obtaining the stress-strain relationship for a material. The shear stress and shear strain are obtained directly in the torsion test. Since the primary deformation of ductile materials is by shear, the torsion test has direct applicability to the normal condition cladding performance.

Table 13 DE.04 SNTT summary

Objective	Measure the fracture toughness of the fuel system. Assess, as possible, the strength of the pellet-cladding bond.
Initial conditions	Fueled segments; T0, FHT, SEG, SEG-REWET
Sample size	4 in. segment
Number of samples	30
Information or benefit obtained	Data for simulation and prediction of fuel performance during dynamic conditions (e.g., transportation and off-normal/accident conditions).
	Data on the clad-pellet interface bonding efficiency (torsion).
	Determination of the DBTT (Phase II provides baseline performance at room temperature conditions; Phase III provides data with temperature variation).
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

SNTT has been applied to ductile and brittle materials as well as composite materials [14]. The testing protocol based on the SNTT methodology and the equipment used are illustrated in Figure 10. Previous studies showed that the principal tensile stress (opening mode) is perpendicular to the 45° spiral groove line and that crack propagation is toward and perpendicular to the specimen central axis. Figure 10c provides an example of a fractured SNTT test specimen, Figure 10d compares and contrasts the SNTT specimen and loads with the traditional CT specimen, and Figure 10e and f illustrate the test setup with an example of and alumina oxide coated SNTT sample.

Fracture toughness (KIC) and dynamic fracture toughness (KID) are also derived from the SNTT. A distinct advantage of the SNTT fracture toughness testing protocol is that the small cylindrical specimen requires very little preparation as compared with other impact toughness test specimens, which must be constructed from cladding pieces.



a) schematic of the theory b) SNTT fracture test setup c) halves of tested A302B specimens

d) Charpy type (top) vs. SNTT type (bottom) specimen e) SNTT coating test setup f) U-grooved spiral coating test

Figure 10. Spiral notch toughness test theory and test equipment.

The SNTT can also be used to evaluate clad-pellet bonding effects on SNF system performance through comparative testing of as-received specimens, others that have been cyclically heated and pressurized, and others that have been subjected to vibrational loads mimicking those encountered during transport.

Fueled samples will be tested. Defueled samples may be tested if the fueled sample testing indicates it is necessary. The properties derived from the test include:

- modulus of rigidity in shear
- modulus of rupture in shear
- yield shear strength
- ultimate shear strength
- elongation in torsion
- mode of fracture (ductile or brittle)

The test is usually performed in a quasi-static mode, meaning loads are changed very slowly. The test is also used to categorize materials as ductile or brittle based on the rupture plane. Temperature studies and faster loading rates are used to define the DBTT (planned for Phase III).

No test protocols are available from the American Society for Testing and Materials (ASTM) for SNTT, as it is a novel protocol recently developed by ORNL specifically for cylindrical shapes.

3.4.2.5 DE.05: CYCLIC BENDING FATIGUE STATIC, DYNAMIC, AND SHOCK TESTS

The cyclic integrated reversible-bending fatigue tester (CIRFT) can be used to perform both static and dynamic fatigue tests [15] and will be used to evaluate mechanical properties, fatigue lifetime, and fatigue lifetime after transient shocks (cumulative test). The tests, summarized in Table 14, will be performed in a manner similar to the testing that has already been completed for different fuel rods [16].

Table 14. DE.05 CIRFT summary

Objective	Apply static, dynamic, and representative impact loads to determine the mechanical properties of the test specimen and to assess the fatigue lifetime of the specimen. If fracture of the specimen occurs, collect any fuel fragments or particles released, as possible.
Initial conditions	Fueled segments; T0, FHT, SEG
Sample size	6 in. segments; one static sample (6 in.) per rod
Number of samples	Nominally 42 6 in. samples allocated. Results will be compared with existing data to evaluate trends. Enough samples will be tested to provide an S-N curve indicating load to failure at a given number of cycles. However, as results are evaluated, the number of samples may be reduced.
Information or benefit obtained	Static data will be used to evaluate material properties for use in simulation of SNF for storage, transport, and disposal.
	Static and dynamic data will be used for comparison with previously obtained data to compare and contrast the relative performance of the fuel system and potential failure limits for different stress modes.
	Dynamic data will be used to assess the fatigue lifetime of the fuel for application in fuel transport.
	Static, dynamic and cumulative data are expected to provide insight to the fuel/clad bond composite structure performance (e.g., as it influences strength following handling drops or transient shocks/vibrations).
	Static and dynamic data are expected to provide insight to the complex loading/stress conditions at the pellet-pellet interfaces.
	As possible, aerosolized radionuclides released as a result of specimen cladding breach will be used to assess the release fractions and specific activities for the contribution to the releasable source term limits for HBU fuel.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

The CIRFT U-frame, shown in Figure 11, includes two rigid arms, connecting plates, and universal testing machine links. The rod specimen is oriented horizontally and is coupled to the rigid arms through two specially designed grips. Linear motions are applied at the loading points of the rigid arms and are converted into pure bending moments exerted on the rod. The CIRFT can deliver dynamic loading to a rod specimen at 5 to 10 Hz. Three linear variable differential transducers measure rod deflections at three adjacent points within the gage section to determine rod curvature, which is then correlated to the applied moment to characterize the mechanical properties of the bending rod. Online monitoring can capture mechanical property changes to reveal fatigue behavior during testing.

A static test is used to identify the moment and curvature at which deformation of the segment occurs and to establish the range of load amplitudes for the dynamic tests. The dynamic tests are typically performed for a fixed amplitude and frequency to identify the number of cycles to failure. After a test, the broken surfaces (if failure occurs) can be examined using optical methods (DE.02, DE.06, DE.13). For the cumulative CIRFT, transient impacts will be applied to the sample, based on the expected typical transport condition, to simulate rod-to-rod and rod-to-basket impacts arising from normal vibration loads. The transient impacts will be applied in a consistent manner.

Selected sister rod specimens will be tested at selected moment amplitude ranges for normal transport and based on the results of previous testing in the CRIFT. Also, limited selected segments, pressurized and depressurized, will be thermally cycled (~10 times) from ambient to selected peak cladding temperatures prior to CIRFT testing to examine the effects of thermal cycling on fatigue performance. Most of the samples will be taken from high-burnup regions; however, some specimens from near the ends of the fuel rod and from under-grid regions will be tested for comparison. These tests are expected to verify assumptions about performance in these regions and with respect to the presence of flaws such as those observed due to GTRF. The Phase II tests will be conducted at room temperature. The specimens will be tested to failure, or testing will be stopped after reaching 10,000,000 cycles.

No ASTM test protocols are available for CIRFT, as it is a novel protocol recently developed by ORNL specifically for composite fuel rod evaluation.

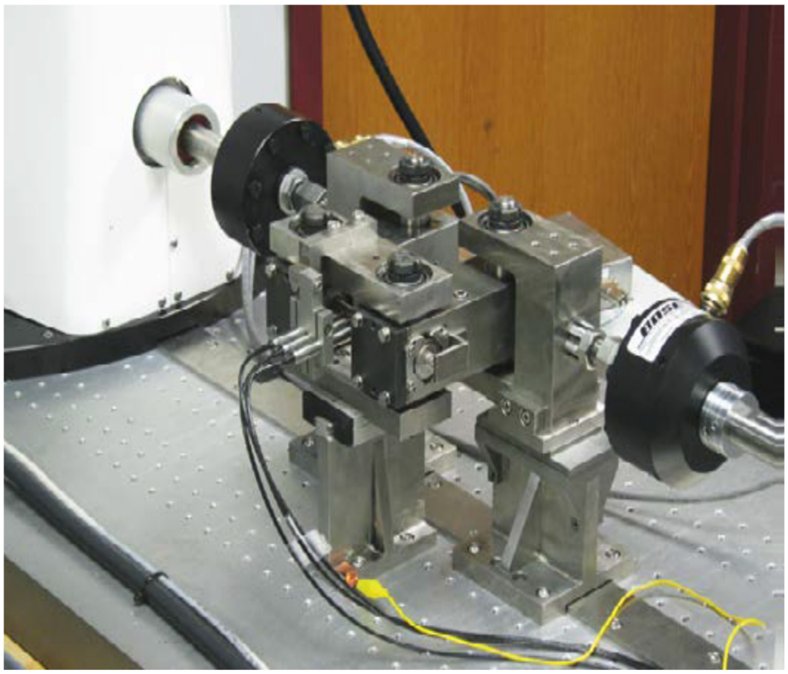


Figure 11. The cyclic integrated reversible-bending fatigue tester.

3.4.2.6 DE.06: SEM EXAMINATION OF FUEL AND CLADDING

The general morphology of the fuel, as illustrated in Figure 12, will be examined using low- and/or high-magnification SEM imaging as needed based on the results of other destructive tests.

Selected rough-cut segments will be further segmented, mounted and polished for examination of pellet cracking, pellet-cladding gap and interface, fission gas bubbles, fuel restructuring and rim effects, clad oxide layer thicknesses (pellet-side and water-side), agglomerate behavior, and fission product profiles. Features of interest may be examined in detail at higher magnifications. As possible, thin mounts will be used to control radiation levels to accommodate the SEM facility needs; size and dose restrictions may limit the size of the regions examined. Table 15 summarizes the DE.06 examinations.

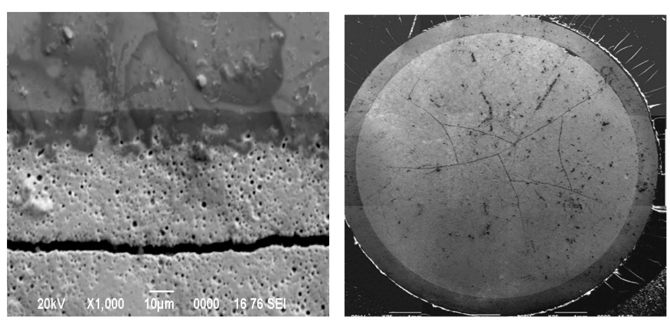


Figure 12. Examples of the level of detail possible using high-magnification (left) and low-magnification (right) SEM imaging.

Also, as needed, SEM microprobe scans using wavelength dispersive spectroscopy (WDS) for Nd will be used to measure local burnup. Local Nd (total and ^{148}Nd) is a good indicator of burnup due to its low mobility in the fuel. It has been demonstrated that the local concentration of Nd increases almost linearly with local burnup [17,18]. However, very small samples are required to maximize signal-to-noise levels.

Table 15. DE.06 SEM summary

Objective	Characterize the general morphology of the fuel and cladding. Characterize the amount of bonding between the fuel and the cladding.
Initial conditions	Fueled and unfueled segments
Sample size	< 0.5 inch
Number of samples	16; specimens to be examined as needed based on the results of other examinations.
Information or benefit obtained	Provides necessary information to characterize the state of the samples and to correlate performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

3.4.2.7 DE.07: 4-POINT BENDING TESTS.

The four-point bending (4PB) flexural test provides values for the modulus of elasticity in bending and the flexural stress and flexural strain response. It is the test traditionally used to study brittle materials, where the number and severity of flaws exposed to the maximum stress is directly related to the flexural strength and crack initiation. The test fixturing, illustrated in Figure 13, is available in the IFEL and is used with the IFEL universal test machine to apply the loads. A summary of the DE.07 tests is provided in Table 16.

Although the information obtained from a 4PB test is more limited in scope and is redundant with other tests, it is needed to provide validation information for those other methods. The 4PB test is used across industries, is well understood, and is simple to perform, whereas the other mechanical tests are specific to SNF examinations. Because some of the equipment used in the SNF testing may not be available (or may need to be rebuilt) when the cask rods are retrieved, it is important to provide a test with tried and true reliability as a benchmark for the program to mitigate risk.

Several ASTM standards are available for 4PB, including *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature* (ASTM C1161), *Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure* (ASTM C393), and *Standard Test Method for Facing Properties of Sandwich Constructions by Long Beam Flexure* (ASTM D7249).

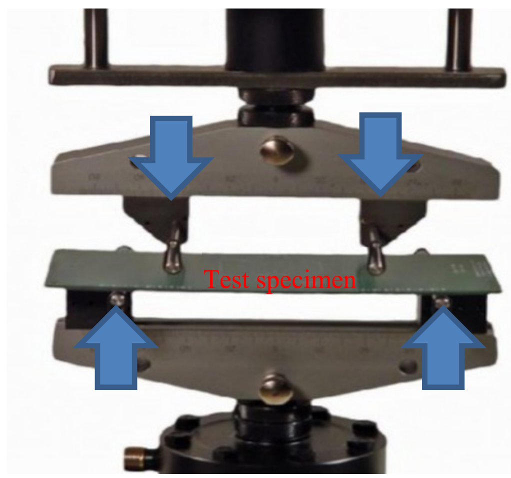


Figure 13. A typical four-point bend test fixture, shown with a flat bar test specimen.

Image: www.testresources.net/ (modified)

Table 16. DE.07 4PB summary

Objective	Apply static loads to determine the mechanical properties of the test specimen
Initial conditions	Fueled segment; T0, FHT, SEG
Sample size	6 in.
Number of samples	36
	Static data will be used for simulation of SNF for storage, transport, and disposal.

Information or benefit obtained	Static data will be used for comparison with data obtained using other tests methods to provide an alternate method and to provide validation.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

3.4.2.8 DE.08: TUBE TENSILE/AXIAL TESTING OF FUEL CLADDING

Table 17 summarizes the DE.08 examinations. Tensile testing is used throughout the world as a basic tool for material property evaluation and selection. The tensile properties of common construction materials such as steel and aluminum have been measured extensively and are typically used as specifications for material quality assurance. For parts loaded in tension, the tensile properties derived from tensile testing can be used directly in assessing performance under many loading conditions. The properties derived include:

- axial yield strength
- ultimate tensile strength
- uniform and total elongation
- Young's modulus
- strain hardening modulus

Tensile testing is often performed using machined "dog-bone" coupons in a quasi-static mode (slowly changing loads). For the sister rods, tensile testing will be performed on full-size cladding samples. As an alternative, micro test coupons can be machined from the cladding. Intact irradiated fuel rod samples will also be tested.

Table 17. DE.08 axial tension summary

Objective	Measure the traditional mechanical properties of the cladding, including Young's modulus, yield strength, strain hardening, ductility, and ultimate tensile strength in the axial direction.
Initial conditions	Defueled segments; T0, FHT, SEG
Sample size	6 in.
Total number of samples	30
Information or benefit obtained	Data will be used for simulation of SNF for storage, transport, and disposal.
	Data will be used for comparison with previously obtained data to compare and contrast the relative performance of the fuel system and potential failure limits for different stress modes.
	Data will be used to determine if the thermal environments imposed during dry storage modify the mechanical properties of the cladding
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

For suitable specimens, the tensile testing may be modified to include a compression sequence. Unfortunately, it is not clear that defueled sister rod cladding specimens can be successfully compression-tested, as they are susceptible to column buckling and/or local buckling during compression loading that could invalidate any results. Since the SNF rods are not subjected to axial compression loads except under accident conditions where column buckling followed by bending fracture is the primary mode of failure, compression testing of defueled cladding is not recommended. Intact fuel rod specimens (pellets and cladding) are expected to be somewhat more stable in compression but still may be subject to buckling/bending failure.

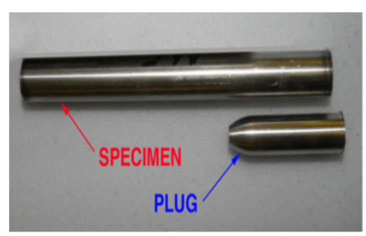


Figure 14. Tensile specimen with filler plug used to provide solid end grips.

To ensure that the range of burnup and hydride content are sampled, several axial locations of each rod will be tested. The Phase II tests will be conducted at room temperature, and the specimens will be tested to failure. Post-test fractographic examination will be performed to characterize the failure regions using an electron microscope, as needed. To prevent crushing of the specimen at the load application points and to provide a solid grip on the ends, metal plugs (shown in Figure 14) will be inserted into each end of the specimen.

Several ASTM test methods have been established for tensile testing, including ASTM E6, ASTM E111, ASTM E646, ASTM E132, ASTM E517, and ASTM E8 which has been used by nuclear fuel vendors for cladding lot acceptance testing.

3.4.2.9 DE.09: MICROHARDNESS TESTING

Hardness can be correlated to tensile strength for many metals and alloys and is also an indicator of machinability, wear resistance, toughness, and ductility. For the sister rod testing, Vickers microhardness (µH) indentions have been specified to explore the difference in the material properties across the cladding thickness and near or in precipitated hydrides. µH indentions can also be used to characterize the pellet high burnup rim friability for application in assessing its vulnerability to damage that would release airborne, and respirable particles. A typical indenter, tooling, and indentions in a UO_2 pellet are illustrated in Figure 15.

Although ORNL has an indenter in lower dose laboratories, it does not currently have an indenter in the IFEL hot cells. The machines are relatively low cost and easy to come by. Microindenters come in benchtop sizes and can be accommodated in a relatively small space. Defueled cladding can be examined for µH using the indenter in the ORNL Low Activation Materials Development and Analysis (LAMDA) facility. Table 18 summarizes the DE.09 examinations to be performed.

Standard Test Method for Microindentation Hardness of Materials (ASTM E384-16) is applicable for Vickers microhardness testing.

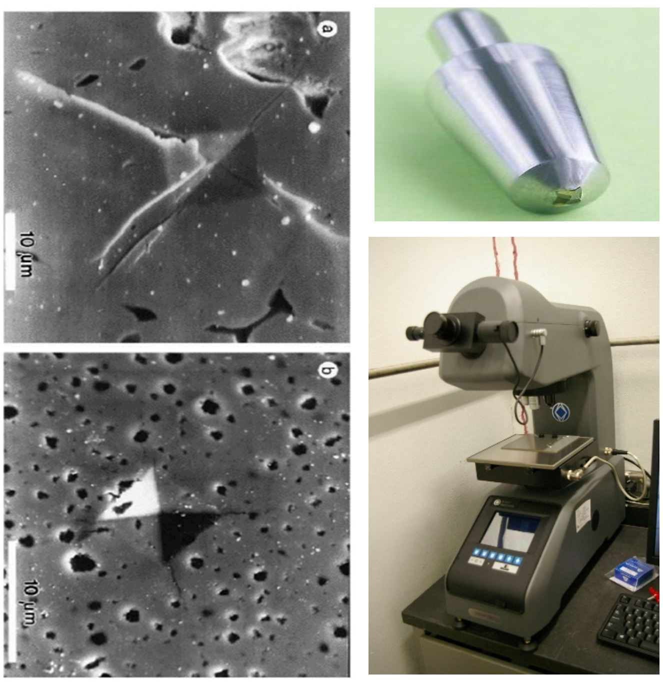


Figure 15. Example of Vickers micro-hardness indentions on UO_2 fuel in a low-burnup region (top left) and a high-burnup region (bottom left) [19]; and a typical Vickers indenter (top right) and indention machine (bottom right).

Table 18. DE.09 µH summary

Objective	Provide an indication of local relative tensile properties of UO_2 and cladding.
Initial Conditions	Fueled and defueled segments; T0, FHT, SEG
Sample size	Samples to be harvested from other specimens
Number of samples	40
Information or benefit obtained	Understanding the radial/local variation in the tensile strength across the fuel rod radius and at selected axial locations. Understanding the localized effects of hydride platelets and pellet high burnup rim porosity.

Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

3.4.2.10 DE.10: RING COMPRESSION TESTING (FUELED AND UNFUELED)

Ring compression test (RCT) loading simulates a “pinch” type loading at grid-spacer springs and fuel-rod contact with grid spacers, with other fuel rods, and with the assembly basket walls. The sample is loaded in lateral compression (i.e., in the radial direction), inducing hoop bending stresses in the cladding. Testing of as-irradiated cladding will provide baseline data for comparison with the cask rods. Additionally, FHT, SEG, and SEG-REWET heat treatments will be applied to selected specimens, and RCT may be completed at temperatures other than room temperature to define the DBTT. All ANL RCTs are considered to be SEG heat-treated specimens. RCTs will be conducted with fueled and defueled cladding specimens. The load-displacement curves for fueled vs. defueled cladding samples will be compared to assess the support provided by the pellet.

RCT of defueled specimens will be performed at ANL in a similar manner to previous RCTs [11,12]. A minimum of twenty-one 3.5 in. T0 segments will be defueled at ORNL and shipped to ANL, where they will be further segmented to produce RCT specimens for testing per Figure 16. For each 3.5 in. segment of cladding, ANL will perform supporting MET/H_2 and total hydrogen measurements (DE.02 and DE.03) for each segment; a portion of each RCT rough-cut segment is included specifically for this purpose (both pre- and post-heat treatment). ORNL will not perform DE.02 or DE.03 examinations on specimens provided to ANL to avoid duplication; instead, they will be performed at ANL, and ANL will provide the results to ORNL. For specimens tested at ORNL, both DE.02 and DE.03 will be completed on nearby representative specimens (see the cutting plan in Appendix A).

In addition to the 21 ANL RCT segments, six selected FHT RCT specimens will be defueled and provided to ANL to undergo RCTs as a priority for evaluation in conjunction with other FHT evaluations. For FHT cladding samples, the extent of radial hydride precipitation will be characterized, and, if warranted, an RCT temperature study to determine the DBTT may be completed. At least one ring from each FHT segment will be tested as received at ANL. The remainder of the FHT segments will be held in reserve pending the results of the initial tests. If further FHT RCT is deemed unnecessary (concurrence by ORNL and ANL sister rod project leads), ANL may use the remainder of the specimens for other purposes.

105E1: Pre-test MET (DE.02), with the remainder reserved for future use
105E2: Hydrogen content sample (2 mm) (DE.03)
105E3: Ring-compression test sample (8 mm) (DE.10)
105E4: Ring-compression test sample (8 mm) (DE.10)
105E5: Hydrogen content sample (2 mm) (DE.03)
105E6: Met sample (3 mm) (DE.02)
105E7: Ring-compression test sample (8 mm) (DE.10)
105E8: Ring-compression test sample (8 mm) (DE.10)
105E9: Hydrogen content sample (2 mm) (DE.03)
105E10: Reserved for future use (≈ 45 mm)

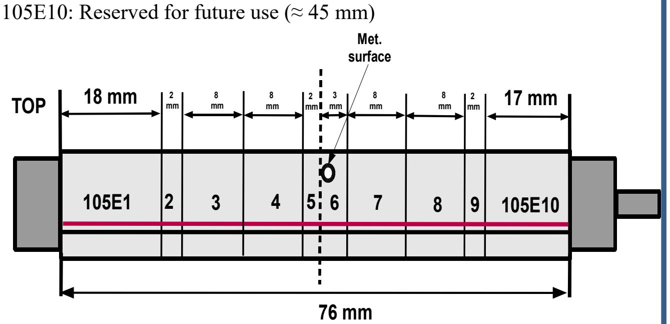


Figure 16. Cutting diagram for rough cut segments to be used at Argonne National Laboratory for ring compression testing.

Although it is not necessary to test fueled samples to failure, cladding failure (through-wall crack) or partial failure may occur. Selected post-test specimens will be examined optically (DE.02, DE.06, and/or DE.13) to characterize crack surfaces and the extent of radial hydride precipitation.

At present, there is no ASTM protocol for RCT, as it was developed by ANL specifically for use with irradiated fuel cladding. Table 19 provides a summary of the DE.10 examinations to be completed.

Table 19. DE.10 RCT summary

Objective	Measure the traditional mechanical properties, including Young's modulus, yield strength, strain hardening, ductility, and ultimate tensile strength in the lateral direction.
Initial conditions	Both fueled and defueled segments; T0, FHT, SEG, SEG-REWET.
Sample size	3.5 in. segments with 8 mm subsamples (see Figure 16)
Number of samples	10 fueled and 37 defueled samples
Information or benefit obtained	Fueled and unfueled mechanical properties supporting modeling and simulation of fuel during storage and transportation, including the hoop stress vs. plastic strain properties of the cladding materials, as well as the engineering values for YS, UTS, and UE. It is important to conduct the test with all four cladding alloys because the database is rather sparse for the temperature range of interest.
	For fueled segments subjected to simulated drying storage, the extent of radial hydride precipitation will be characterized, and RCTs will be performed to determine possible degradation in properties due to radial hydrides.
	The test may identify conditions for subsequent fracture toughness conditions (due to an increase in the DBTT induced through the heat treatments applied).
	Mechanical property data are particularly important for M5® cladding for which publicly available data are inadequate. It is also important for the other alloys because the database is rather sparse for the temperature range of interest.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling (selected specimens); capped and pressurized (fueled segments)

3.4.2.11 DE.11: EXPANDED CONE-WEDGE TESTING

The expanded cone-wedge (ECW) test method uses an expandable cone and wedge setup and dual pistons drivers to stretch a small ring of the clad tubing material. The test setup with a test sample is illustrated in Figure 17.

The ECW test provides an effective means for determining the quasi-static hoop strength of HBU SNF. The specimen strain is determined using the measured diametrical expansion of the ring. An analytical protocol developed at ORNL is used to convert the measured strain data from the ECW tests into material stress-strain curves.

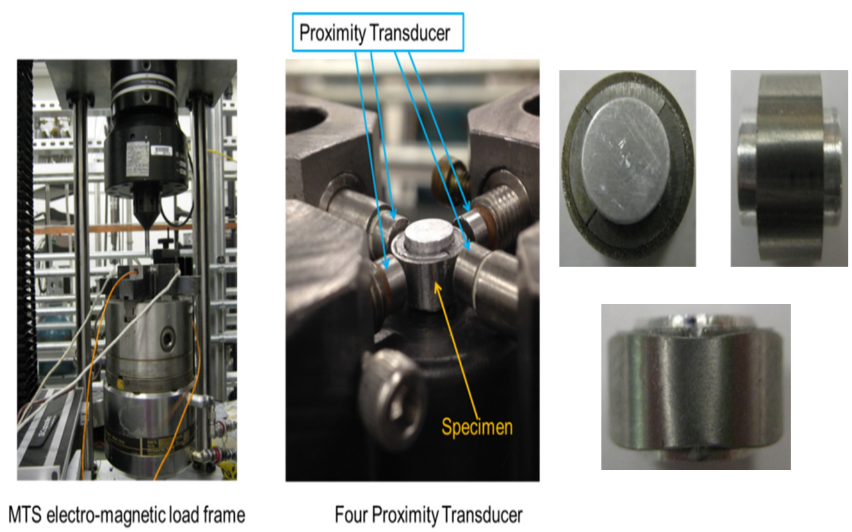


Figure 17. Expanded cone-wedge test setup with specimen shown.

This newly developed testing protocol removes many complexities associated with specimen preparation and testing. The advantages are simplicity of test component assembly in the hot cell and the direct measurement of specimen strain. The quasi-static load application and frictional boundary condition is more applicable to normal storage and transport conditions than other internal pressure application tests. Currently, this method has been successfully applied to Zr-4 and M5 clad tubing materials. Table 20 provides a summary of the DE.11 examinations.

Table 20. DE.11 ECW summary

Objective	Measure the tensile properties of a tubing structure in the tangential direction (i.e., hoop strength), including Young's modulus, yield stress, and strain hardening behavior.
Initial Conditions	Defueled segments; T0, FHT, SEG
Sample size	0.5 in.
Number of samples	30
Information or benefit obtained	Understanding the various stress parameters and the associated mechanical properties, including hoop stress behavior, is important to support modeling of SNF reliability.
	Evaluation of the hoop strength with a uniaxial load application provides more definitive results than biaxial testing.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

3.4.2.12 DE.12: EMISSIVITY

Measurements of the waterside surface emissivity (ε) can be taken by comparing the temperature of the as-received surface with an area where a thin layer of a high-emissivity coating has been applied (paint, tape, or other material with known emissivity). The surfaces are allowed to come to thermal equilibrium (and may also be heated using a radiant heat source) and the temperatures are measured using an infrared (IR) thermometer. First the IR thermometer is set with the known emissivity of the coating and the coated area is measured. The uncoated surface is then measured, adjusting the thermometer's emissivity setting until the temperature reads the same on the uncoated surface. The value obtained is the uncoated surface's emissivity. Several different waterside surface conditions such as typical oxide, spalled oxide, and CRUD can be evaluated. Table 21 provides a summary of the DE.12 examinations.

Challenges to be overcome include the selection of the coating, application of the coating to the rod, and use of the IR thermometer in the hot cell. Because the coating can potentially invalidate the specimen for other testing, a limited number of specimens will be evaluated. Others will be added as necessary/desired.

Table 21. DE.12 ε summary

Objective	Measure the waterside surface emissivity given various rod surface conditions (oxidized, spalled, CRUD)
Initial Conditions	Fueled segments; SEG
Sample size	To be selected from post-test samples (as possible)
Number of samples	3
Information or benefit obtained	Fuel rod waterside surface emissivity for use in thermal simulations.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, initially specified testing completed (emissivity testing to be completed on selected waste segments).

3.4.2.13 DE.13: TRANSMISSION ELECTRON MICROSCOPY

Transmission electron microscopy (TEM) is used to examine the long–term aging effects on the irradiated microstructure of the cladding and fuel/clad interface. Figure 18 provides an example of the specimen preparation required for TEM. Typically, samples are taken from mechanical test specimens or other specimens as needed pre- or post-mechanical test. Specific items examined through TEM include any changes to radiation-induced defects (a- and c-type component loops) in response to any low-strain deformation, hydride development or reorientation, fuel/clad interaction, solute segregation and changes to precipitate structures.

Observations with the TEM will be used in conjunction with mechanical test results to better understand how microstructural changes influence mechanical integrity and will be specified as needed. Work may include some atom probe tomography on select samples or rod conditions to complement the TEM analyses. This portion of the work will involve the LAMDA laboratory at ORNL. Table 22 summarizes the DE.13 examinations.

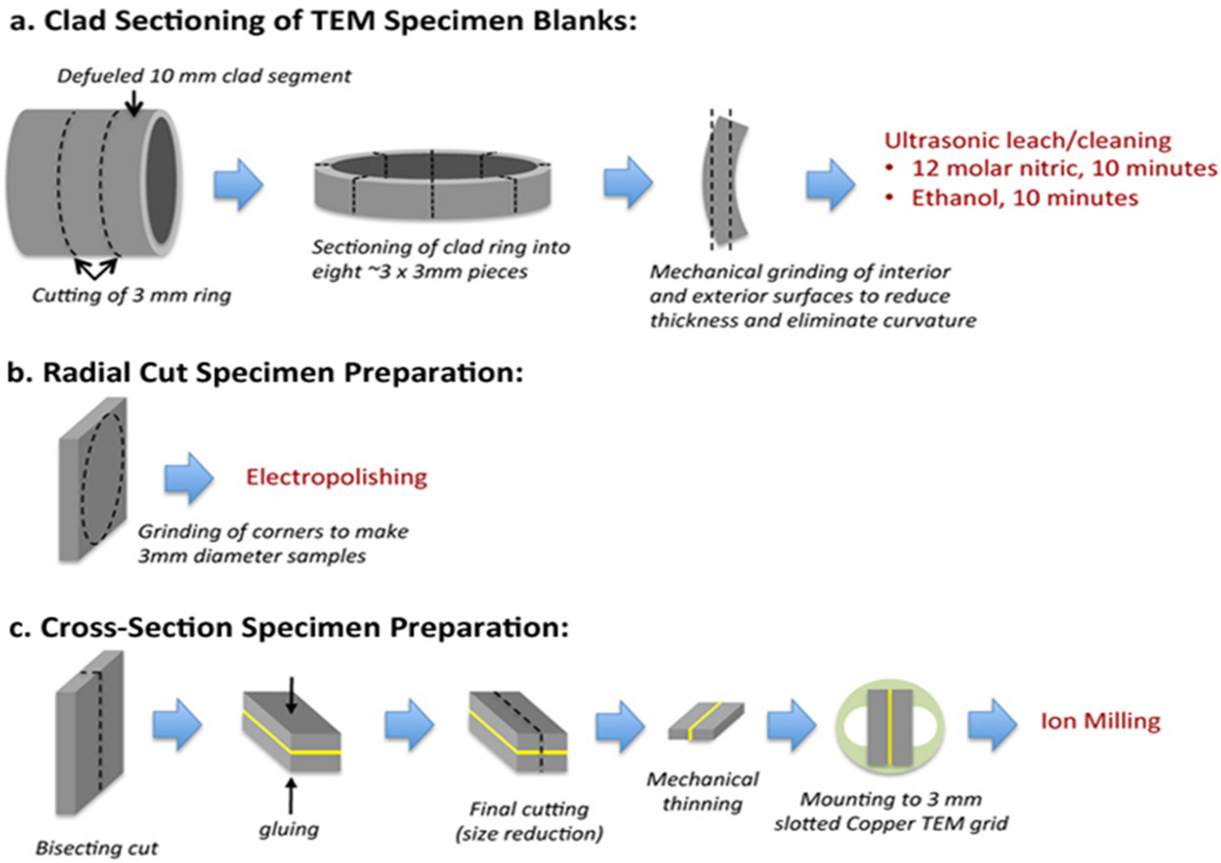


Figure 18. Sample preparation for TEM examination includes sectioning of the rough cut segment and mechanical thinning to remove curvature and reduce thickness, followed by mounting.

Table 22. DE.13 TEM summary

Objective	Characterize the general morphology of the fuel and cladding. Characterize the amount of bonding between the fuel and the cladding.
Initial conditions	Fueled and unfueled segments
Sample size	<<0.5 in.
Number of samples	4; specimens to be examined as needed based on the results of other examinations.
Information or benefit obtained	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

3.4.2.14 COLLECTION OF FUEL FRAGMENTS OR PARTICLES FOLLOWING TEST SPECIMEN CLAD FRACTURE

It is recommended that during performance of dynamic sister rod examinations, as possible, aerosolized radionuclides released upon segment breach be captured and quantified and that the particle distribution be determined. The data will be used to assess the release fractions and specific activities for the contribution to the releasable source term limits for HBU fuel. In particular, data for aerosolized radionuclides and particle distribution can be collected from CIRFT, SNTT, and 4PB tests, where energetic fracture of the test specimen is expected. An initial concept for collection of the particles includes pre- and post-examination weighing and a bullet-proof enclosure with a flowing inert gas purge for aerosol collection and filtration.

3.5 APPLICATION OF THE DATA

The goal of this work is to provide data addressing the gaps to extended dry storage of HBU SNF. To illustrate the separate effects of burnup, temperature, and other conditions, it is necessary to group the test specimens with other comparable specimens. This section provides an initial listing of the expected groups for comparative evaluation of the results of the sister rod DE.

3.5.1 CHARACTERIZATION OF SPECIMENS FOR CORRELATION WITH RESULTS

The draft cutting plan provided in Appendix A allocates specimens for each DE and is intended to provide both duplication and variation with respect to the macroscopic rod condition (clad oxide layer thickness and hydride content, cladding metallographic structure, fuel burnup and microstructure, CRUD) as discussed in Section 3.4.1. The NDE provides information on locations of CRUD and wear marks, burnup distribution, and oxide thickness. Optical examinations (DE.02 MET/H_2) are specified at regular locations along each rod's axis to provide information on these parameters for correlating DE results. As necessary to properly characterize the test specimen, both pre- and post-DE optical examinations may be included (e.g., all ANL RCT segments include material for this purpose). This is particularly important for DE where the results are expected to trend with hydride orientation or other parameters that may be changed by heat treatment or by the DE itself.

3.5.2 BASELINE SISTER ROD DATA COMPARISONS WITH CASK ROD DATA

The direct comparison of the baseline sister rods with the cask rods and with the heat-treated sister rods will help identify degradation (or recovery) in mechanical performance of the HBU SNF resulting from dry storage. Table 1 and Table 2 list the cask rods paired with each sister rod for direct post-storage comparisons. It is further expected that cask rod (T10) DE specimens will be paired with the sister rod specimens for direct comparison after the dry storage demonstration period.

The DE performed and axial locations of the baseline rod specimens should be closely matched with corresponding specimens from the paired cask rod, as guided by cask rod NDE, to allow for direct comparison of measured properties and performance. For example, for cask rod 3U4I07 paired with sister rod 6U3I07, the DE and cutting plan provided by Appendix A Figure A-2 should be utilized as the initial plan for examinations, with cutting elevations adjusted as needed based on 3U4I07 NDE.

Final selections for comparison pairing of the cask rods with the sister rods should incorporate information on the measured local cladding oxide thickness and hydrogen content (see section 3.5.1) along with burnup, decay heat, and other parameters (as necessary) to provide more precise pairs for comparison of DE results.

3.5.3 BASELINE SISTER ROD DATA COMPARISONS WITH OTHER T0 SISTER ROD DATA

A primary objective of the baseline testing is to determine the essential mechanical properties as a function of rod burnup, dry storage time, and exposure to temperature cycling (termed "cladding stress profiles"), including clad ductility, modulus of elasticity, Poisson's ratio, ultimate tensile strength (UTS), yield stress (YS), and uniform elongation (UE). The collected data can be used to understand what stresses and conditions result in fuel rod failure and to better define typical conditions for HBU fuel. The data will be used in conjunction with measurements of forces and stresses imposed on the fuel rod to close the stress profiles gap. The sister rod test plan includes testing to provide baseline mechanical properties supporting the calculation of cladding stress profiles at the pre-dry storage condition. The effects of oxidation can be evaluated through measuring, analyzing, and comparing the DE results for several sister rod samples.

Also, testing supporting transportation of SNF is included to establish the fatigue strength and fracture toughness of the HBU SNF rod, along with the effects of rod-to-rod or rod-to-basket impacts resulting from normal transport. An understanding of the role of the fuel in maintaining rod integrity is provided through a comparison of the fueled rod specimen test results with defueled material property data (primarily provided through previous cladding data and further supported by data from DE.09, DE.10 and DE.11).

Although the data obtained though the sister rod DE can be compared and contrasted in many combinations, the initial baseline data comparison groups are presented in Table 23. Groups of specimens for comparison and contrast of measured baseline mechanical properties from DE.04, DE.05, DE.07, DE.08, DE.09, DE.10 and DE.11 were selected based on each specimen's estimated average burnup. A test specimen in every subgroup is not available due to the limited SNF material and budget.

Table 23. Baseline data comparison groups

Group ID/Subgroup ID		Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BZDE.04	4050	3D8E1433333436	40 to 50	Zirlo	Mechanical properties – fueled
	5055	3D8B0204500553 3D8B0230533156 3D8B0217031806 6U3I0731533256	50 to 55	Zirlo	Mechanical properties - fueled
	5560	3D8E1403280431	55 to 60	Zirlo	Mechanical properties - fueled
	60+	3D8E1411191222 6U3I0719892092	60 and higher	Zirlo	Mechanical properties - fueled
BMDE.04	5560	5K7O1421692272	55 to 60	M5	Mechanical properties - fueled
	60+	30AD0505430646 30AD0521432246 5K7O1411041207 5K7O1415471650 30AE1411041207 30AE1415471650 30AE1421692272	60 and higher	M5	Mechanical properties - fueled
	poison comp	30AD0505430646 30AD0521432246 30AE1411041207 30AE1415471650	~65	M5	Mechanical properties – fueled, comparison of D-5 & E-14 operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.04	5560	3A1B1610641167 3A1B1615271630 3A1B1617971900	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties – fueled

Table 23. Baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BZDE.05	5055	3D8B0229003053 3D8E1431803333	50 to 55	Zirlo	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
	5560	6U3I0730003153	55 to 60	Zirlo	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
	60+	3D8B0213831536 3D8B0215501703 3D8B0220042157 6U3I0708901043 6U3I0710571210 6U3I0724122565 6U3I0725832736 3D8E1406600813 3D8E1408130966 3D8E1409661119 3D8E1415741727	60 and higher	Zirlo	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
BMDE.05	4050	30AD0534653618	40 to 50	M5	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
	5055	30AD0503000453	50 to 55	M5	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
	60+	30AD0525942747 5K7O1407800933 5K7O1413041457 5K7O1425642717 30AE1407800933 30AE1413041457 30AE1425592712	60 and higher	M5	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
	Poison comp	30AD0525942747 30AE1407800933 30AE1413041457 30AE1425592712	~65	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.05	5560	3A1B1607400893 3A1B1612841437 3A1B1624472600	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled
BZDE.07	5560	6U3I0704640617	55 to 60	Zirlo	Mechanical properties - fueled
	60+	3D8B0209901143 3D8B0224952648 3D8E1414071560 3D8E1418942047 3D8E1424472600	60 and higher	Zirlo	Mechanical properties - fueled
B4DE.07	5560	3A1B1607400893 3A1B1612841437 3A1B1624472600	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties, fatigue strength, fracture toughness, effect of shocks - fueled

Table 23. Baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BZDE.07	5560	6U3I0704640617	55 to 60	Zirlo	Mechanical properties - fueled
	60+	3D8B0209901143 3D8B0224952648 3D8E1414071560 3D8E1418942047 3D8E1424472600	60 and higher	Zirlo	Mechanical properties - fueled
BMDE.07	60+	30AD0509271080 30AD0514711624 30AD0519762129 5K7O1409511104 5K7O1418171970 5K7O1420022155 30AE1409511104 30AE1418171970 30AE1420022155	60 and higher	M5	Mechanical properties - fueled
	Poison comp	30AD0509271080 30AD0514711624 30AD0519762129 30AE1409511104 30AE1418171970 30AE1420022155	~65	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.07	4050	3A1B1628402993	40 to 50	Zirc-4 and LT Zirc-4	Mechanical properties - fueled
	5560	3A1B1609111064 3A1B1620802233	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties - fueled
BZDE.08	4050	3D8E1434363589 3D8B0231563309	40 to 50	Zirlo	Mechanical properties - fueled
	5560	3D8E1404450598	55 to 60	Zirlo	Mechanical properties - fueled
	60+	3D8B0223242477 6U3I0720922245 3D8E1421272280	60 and higher	Zirlo	Mechanical properties - fueled
BMDE.08	5055	30AD0532843437	50 to 55	M5	Mechanical properties - fueled
	5560	30AD0522462399	55 to 60	M5	Mechanical properties - fueled
	60+	5K7O1405240677 5K7O1422722425 30AE1405240677 30AE1422722425	60 and higher	M5	Mechanical properties - fueled
	Poison comp	30AD0532843437 30AD0522462399 30AE1405240677 30AE1422722425	55 and higher	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.08	4050	3A1B1604720625	40 to 50	Zirc-4 and LT Zirc-4	Mechanical properties - fueled
	5055	3A1B1622802433	50 to 55	Zirc-4 and LT Zirc-4	Mechanical properties - fueled
BZDE.09	4050	6U3I0734373441 3D8E1402340238 3D8E1435893593 3D8B0233093313	40 to 50	Zirlo	Mechanical properties - defueled
	5560	6U3I0707060710 6U3I0717061710	55 to 60	Zirlo	Mechanical properties - defueled

Table 23. Baseline data comparison groups (continued)

Group ID	Subgroup ID	Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BZDE.09	60+	3D8B0208060810 3D8B0218061810 3D8B0224912495 3D8E1412221226 6U3I0725652569 3D8E1421232127	60 and higher	Zirlo	Mechanical properties - defueled
BMDE.09	5055	30AD0532803284 30AE1431903194	50 to 55	M5	Mechanical properties - defueled
	Poison comp	30AD0532803284 30AE1431903194	50 to 55	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
	5560	5K7O1419982002 30AE1419982002	55 to 60	M5	Mechanical properties - defueled
	60+	30AD0513001304 30AD0519721976 30AD0523992403 5K7O1409330937 5K7O1413001304 5K7O1429222926 30AE1409330937 30AE1413001304	60 and higher	M5	Mechanical properties - defueled
	Poison comp	30AD0513001304 30AD0519721976 30AD0523992403 30AE1409330937 30AE1413001304	~65	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.09	4050	3A1B1604400444 3A1B1630213025	40 to 50	Zirc-4 and LT Zirc-4	Mechanical properties - defueled
	5560	3A1B1608930897 3A1B1612801284	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties - defueled
BADE.10	4067	3D8E1430903180 3D8B0208100900 3D8B0218101900 6U3I0707100800 30AD0531903280 5K7O1431203210 30AE1431003190 5K7O1414571547 30AE1414571547 3D8E1402380328 3A1B1619902080	40 to 67	M5 Zirlo Zirc-4 LT Zirc-4	Defueled RCT in as-received condition to establish pre-storage DBTT
	Poison comp	30AD0531903280 30AE1431003190	~55	M5	Defueled RCT D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
	5060	3A1B1614371527 30AD0504530543 6U3I0717101800	Mid-50s	M5 Zirlo Zirc-4 LT Zirc-4	Fueled RCT for comparison to determine pellet contribution to crush resistance in pinch load scenario

Table 23. Baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BZDE.11	40-	6U3I0734233437 3D8E1436073621	40 and below	Zirlo	Mechanical properties - defueled
	5560	3D8E1404310445	55 to 60	Zirlo	Mechanical properties - defueled
	60+	3D8B0212961310 3D8B0219902004 3D8B0224772491 6U3I0710431057 6U3I0725692583	60 and higher	Zirlo	Mechanical properties - defueled
BMDE.11	4050	30AD0534373451	40 to 50	M5	Mechanical properties - defueled
	5055	30AE1431943208	50 to 55	M5	Mechanical properties - defueled
	5560	5K7O1419841998	55 to 60	M5	Mechanical properties - defueled
	60+	30AD0519581972 30AD0525802594 5K7O1425502564 5K7O1429262940 30AE1425452559	60 and higher	M5	Mechanical properties - defueled
	Poison comp	30AD0519581972 30AD0525802594 30AE1425452559	~65	M5	D-5 & E-14 were operated in a guide tube adjacent location with (E-14) and without (D-5) burnable poisons.
B4DE.11	4050	3A1B1604440458 3A1B1630073021	40 to 50	Zirc-4 and LT Zirc-4	Mechanical properties - defueled
	5560	3A1B1624332447	55 to 60	Zirc-4 and LT Zirc-4	Mechanical properties - defueled

3.5.4 BASELINE SISTER ROD DATA COMPARISONS WITH T1 SISTER ROD DATA

An objective of the sister rod examinations is to observe any changes in the SNF rod response resulting from elevated SNF temperatures prior to T1. As discussed in section 3.4.1.5, specimens have been selected from the sister rods to support specific comparisons for immediate application to the technical gaps to extended dry storage and transportation of SNF. In particular, the T1 sister rod data collected allow for examining the effects of temperature, temperature cycling, and subsequent cooling rate on HBU SNF. Data collected will allow for a better understanding of the effect of cladding hydrides and the effects of reorientation of the hydrides. Cladding fatigue caused by temperature fluctuations can also be evaluated through a comparison of segments that have been thermally cycled with segments that have not been cycled. For this purpose, heat treatments are applied to selected SNF and data from mechanical DE are compared directly with other data collected from the sister rods that were not heat treated. Table 24 provides a summary of the data comparisons envisioned.

Table 24. T1 and baseline data comparison groups

Group ID	Subgroup ID	Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
FZDE.04	50+	**6U3M0930733176** **6U3M0903600463** 3D8B0204500553 3D8B0230533156 3D8B0217031806 6U3I0731533256 3D8E1403280431 6U3I0719892092	50 and higher	Zirlo	Prototypical effect of T1 conditions (full length rod, single heating cycle to peak of ~325°C followed by slow cooling at approximately 5°C/hr); majority of specimens in mid-50 burnup range
FMDE.04	55+	**30AG0932003303** **30AG0905370640** 30AD0505430646 30AD0521432246 5K7O1411041207 5K7O1415471650 30AE1411041207 30AE1415471650	55 and higher	M5	Prototypical effect of T1 conditions; majority of specimens in mid-60 burnup range
F4DE.04	55+	**F35P1710641167** **F35P1714311534** **F35P1717971900** 3A1B1610641167 3A1B1615271630 3A1B1617971900	55 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions; LT Zirc-4 at T0, Zirc-4 at FHT condition
SZDE.04	6070	**6U3I0712971400** 6U3I0719892092 3D8E1411191222	Mid-60	Zirlo	Effect of other T1 conditions; segment temperature and pressure TBD
FZDE.05	5065	**6U3M0929203073** 6U3I0730003153 3D8B0213831536 3D8B0215501703 3D8B0220042157	50 to 65	Zirlo	Prototypical effect of T1 conditions on fatigue lifetime
	65+	**6U3M0913041457** **6U3M0914711624** **6U3M0920042157** 6U3I0708901043 6U3I0710571210 6U3I0724122565 6U3I0725832736 3D8E1406600813 3D8E1408130966 3D8E1409661119 3D8E1415741727	65 and higher	Zirlo	Prototypical effect of T1 conditions on fatigue lifetime
F4DE.05	55+	**F35P1707400893** **F35P1712781431** **F35P1725802733** **F35P1702800433** **F35P1730213174** 3A1B1607400893 3A1B1612841437 3A1B1624472600	55 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions on fatigue lifetime; LT Zirc-4 at T0, Zirc-4 at FHT condition

Table 24. T1 and baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
FMDE.05	50+	**30AG0902800433** **30AG0913111464** **30AG0914641617** **30AG0925692722** 30AD0503000453 30AD0510941247 30AD0525942747 5K7O1407800933 5K7O1413041457 5K7O1425642717 30AE1407800933 30AE1413041457 30AE1425592712	50 and higher	M5	Prototypical effect of T1 conditions on fatigue lifetime
STCDE.05	50+	**TBD**	50 and higher	M5, Zirlo, Zirc-4 and LT Zirc4	Effect of 10+ thermal cycles on fatigue performance
FZDE.07	50+	**6U3M0921572310** **6U3M0909801133** **6U3M0925872740** 6U3I0715531706	50 and higher	Zirlo	Prototypical effect of T1 conditions; majority of specimens in mid-50 burnup range
FMDE.07	55+	**30AG0909871140** **30AG0918311984** **30AG0920022155** 30AD0509271080 30AD0514711624 30AD0519762129 5K7O1409511104 5K7O1418171970 5K7O1420022155 30AE1409511104 30AE1418171970 30AE1420022155	55 and higher	M5	Prototypical effect of T1 conditions; majority of specimens in mid-60 burnup range
F4DE.07	55+	**F35P1728402993** 3A1B1609111064 3A1B1620802233	55 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions; LT Zirc-4 at T0, Zirc-4 at FHT condition
FZDE.08	50+	**6U3M0931763329** **6U3M0904770630** **6U3M0924162569** 3D8E1404450598 3D8B0223242477 6U3I0720922245 3D8E1421272280	50 and higher	Zirlo	Prototypical effect of T1 conditions; majority of specimens in mid-50 burnup range
FMDE.08	55+	**30AG0908200973** **30AG0922722425** 30AD0532843437 30AD0522462399 30AE1405240677 30AE1422722425	55 and higher	M5	Prototypical effect of T1 conditions; majority of specimens in mid-60 burnup range

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
F4DE.08	50+	**F35P1704650618** **F35P1715481701** **F35P1722472400** 3A1B1622802433	50 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions; LT Zirc-4 at T0, Zirc-4 at FHT condition

Table 24. T1 and baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
FZDE.09	4550	**6U3M0933293333** 3D8B0233093313	45 to 50	Zirlo	Prototypical effect of T1 conditions
	60+	**6U3M0907960800** **6U3M0913001304** **6U3M0925832587** 6U3I0725652569 3D8E1421232127	60 and higher	Zirlo	Prototypical effect of T1 conditions
FMDE.09	50+	**30AG0933033307** **30AG0919982002** **30AG0913071311** **30AG0924252429** 30AD0532803284 30AE1431903194 30AD0513001304 30AD0519721976 30AD0523992403	50 and higher	M5	Prototypical effect of T1 conditions
F4DE.09	55+	**F35P1704330437** **F35P1722332237** **F35P1708930897** **F35P1712741278** 3A1B1604400444 3A1B1630213025 3A1B1608930897 3A1B1612801284	55 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions; LT Zirc-4 at T0, Zirc-4 at FHT condition
FZDE.11	60+	**6U3M0912861300** **6U3M0919902004** **6U3M0925692583** 6U3I0710431057 6U3I0725692583	60 and higher	Zirlo	Prototypical effect of T1 conditions
FMDE.11	55+	**30AG0909730987** **30AG0925552569** 30AD0519581972 30AD0525802594	55 and higher	M5	Prototypical effect of T1 conditions
F4DE.11	55+	**F35P1704370451** **F35P1730073021** **F35P1712601274** 3A1B1604440458 3A1B1630073021 3A1B1624332447	55 and higher	Zirc-4 and LT Zirc-4	Prototypical effect of T1 conditions; LT Zirc-4 at T0, Zirc-4 at FHT condition

Table 24. T1 and baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
SSRDE.07	60+	**30AD0507600913** **30AD0513041457** **30AD0517911944** **3D8E1412401393** **3D8E1417271880** **3D8E1422802433** **3D8B0209901143** **3D8B0224952648** **30AD0509271080** **30AD0514711624** **30AD0519762129** **5K7O1409511104** **5K7O1418171970** **5K7O1420022155** **30AE1409511104** **30AE1418171970** **30AE1420022155** **6U3I0722452398** **3D8E1414071560** **3D8E1418942047** **3D8E1424472600**	60 and higher	M5 Zirlo	Effect of thermal cycle with peak cladding temperature followed by slow cooling to an intermediate temperature followed by quench in water (SEG-REWET) compared with T0 and FHT

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
SADE.10 Note: **bold** specimens are heat treated and tested by ANL; **<u>bold underline</u>** specimens are FHT specimens tested at ORNL; ***bold italic*** specimens are FHT specimens tested at ANL	50+	**30AD0529403030** **30AD0531003190** **30AE1428402930** **30AE1429303020** **<u>30AG004330523</u>** **30AG0928402930** ***30AG0929303020*** **<u>30AG0930203110</u>** ***30AG0931103200*** **3A1B1619001990** **3D8B0209000990** **3D8B0219001990** **3D8B0227202810** **3D8B0228102900** **3D8E1426002690** **3D8E1426902780** **3D8E1427803000** **5K7O1429403030** **5K7O1430303120** **6U3I0708000890** **6U3I0718001989** **6U3I0727602850** **6U3I0728502940** ***6U3M0908000890*** **<u>6U3M0908900980</u>** **<u>6U3M0918101900</u>** ***6U3M0919001990*** **6U3M0927402830** **6U3M0928302920** **F35P1719001990** **<u>F35P1719902080</u>** ***F35P1724002490*** **<u>F35P1724902580</u>**	50 and higher	M5 Zirlo Zirc-4 LT Zirc-4	Heat treated specimens to various conditions (ANL test matrix not provided in this test plan) to provide a better understanding of the effect of cladding hydrides and the effects of reorientation of the hydrides. Specimens listed in ***bold italic*** and **<u>bold underline</u>** are fueled during FHT and are then defueled for RCT. The remainder are heat treated as defueled cladding specimens. Four specimens will be heat treated (FHT), defueled, and then heat-treated a second time (SEG) by ANL prior to RCT. Specimens shown here will be subdivided to provide four RCT per specimen. This also to be compared to BADE.10.

Table 24. T1 and baseline data comparison groups (continued)

Group ID/Subgroup ID		Specimen ID (T1 specimen in bold)	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
SSRMDE.10	65	**30AG0929303020** **30AG0928402930** **30AD0529403030** **30AD0528502940**	~65	M5	Compare the results of full length heat treat with the same base material processed using SEG and SEG-REWET
SSRZDE.10	65	**3D8E1427803000** **3D8E1430003090** **6U3M0927402830**	~65	Zirlo	Compare the results of full length heat treat with the same base material processed using SEG and SEG-REWET

3.5.5 Baseline Sister Rod Data Comparisons for other expected rod conditions

Commercial SNF is expected to have GTRF wear marks, CRUD, spalled oxide, and other extenuating rod conditions that may influence the performance of the SNF in dry storage and transport. To evaluate any effects of these conditions, sister rod segments identified as having GTRF wear marks, CRUD, or other features will be compared with results from specimens that did not have those issues. Until the NDE is complete, a final listing of specimens cannot be assembled; however, an initial list can be prepared for GTRF based on known vulnerable locations and is provided in Table 25.

Table 25. Potential data groups for GTRF effects

Group ID	Subgroup ID	Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BGTRF	DE.04	3D8B0217031806 6U3I0731533256 3D8E1403280431 3D8E1411191222 30AE1415471650 30AE1421692272 30AG0932003303 30AG0921692272	55 to 60	Zirlo M5	Compare/contrast results for specimens having GTRF wear markings against baseline results.
	DE.05	3D8E1431803333 3D8B0211431296 30AD0510941247 30AD0503000453		Zirlo M5	
	DE.07	6U3I0722452398 3D8E1414071560 3D8B0221572310 6U3I0704640617	55 to 65	Zirlo	

Table 25. Potential data groups for GTRF effects (continued)

Group ID	Subgroup ID	Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
BGTRF	DE.08	6U3I0732563409 3D8B0231563309 30AD0532843437 30AD0516381791 30AD0522462399 5K7O1416641817 30AE1416641817 5K7O1405240677 5K7O1422722425 30AE1405240677 30AE1422722425	Low 50s	Zirlo	Compare/contrast results for specimens having GTRF wear markings against baseline results.
	DE.11	3D8E1412261240 30AE1419841998	50 to 60	Zirlo M5	
FGTRF	DE.05	30AG0902800433 30AG0911541307 6U3M0911331286 3D8B0211431296	55 to 60	Zirlo M5	Compare/contrast results for specimens having GTRF wear markings against

Group ID/Subgroup ID		Specimen ID	Specimen estimated burnup range (GWd/MTU)	Cladding type(s) represented	Comparison objective (see section 3.4.2 for a description of the specific data obtained from each DE)
	DE.07	6U3M0921572310 3D8B0221572310	55 to 60	Zirlo	FHT results.
	DE.08	6U3I0732563409 6U3M0931763329 30AD0532843437 30AG0916641817	55 to 60	Zirlo	
	DE.11	30AG0919841998	Mid-50s	M5	

3.6 PHASE III: FOLLOW-ON EXAMINATIONS TO PHASE I AND PHASE II

Phase III experimental activities will be identified based on data analysis and findings from the Phase I and II activities. Therefore, subsequent to the approval of this document, task-specific planning documents containing operational details and constraints for Phase III will be developed to implement the follow-on activities. The follow-on plans are meant to be phased and adaptive so that they can be implemented to address issues quickly and support informing program direction as new data are available. Current considerations for Phase III involve performing select DE (e.g., DE.04, DE.05, DE.07, DE.08, DE.11) at elevated temperatures.

3.7 PHASE IV: CLEAN UP AND MATERIAL DISPOSAL

As required by the hot cell conduct of operations, the following accompanying hot cell operations will be conducted during and/or after the PIE.

3.7.1 HC.01: WASTE HANDLING

During and after the PIE, waste will be identified, segregated, and packaged for disposal. The waste-handling effort will also require that the appropriate waste paths be identified and that disposal documentation be produced. This activity will involve both the IFEL hot cell and the radiochemical analysis laboratory.

3.7.2 HC.02: SPENT FUEL PACKAGING

The portions of the fuel rods that will not be used in the PIE task will be cut to an appropriate length for disposal and will be packaged for handling. The packaging task will also require the preparation of the necessary paperwork for the material transfer to another building or site. The task will not be executed until the end of the PIE in case additional test specimens are need from the cut segments.

4. INDUSTRY STANDARDS, FEDERAL REGULATIONS, DOE ORDERS, REQUIREMENTS, AND ACCEPTANCE/COMPLETION CRITERIA

This section discusses applicable standards, level of accuracy of activity results, deliverable acceptance criteria, and other requirements as they apply to the work in this test plan.

4.1 CONSENSUS STANDARDS

Consensus standards that may have relevance to some of the detailed activities coordinated within this test plan include:

- ASTM B811-13e1, *Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding*
- ASTM C1161 - 13 *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature*
- ASTM C393 / C393M – 16, *Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure*
- ASTM D7249 / D7249M – 16, *Standard Test Method for Facing Properties of Sandwich Constructions by Long Beam Flexure*
- ASTM E6 – 15, Standard Terminology Relating to Methods of Mechanical Testing
- ASTM E8/E8M - 15a, *Standard Test Methods for Tension Testing of Metallic Materials*
- ASTM E9 - 09, *Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature*
- ASTM E21 - 09, *Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials*
- ASTM E21 – 09, *Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials*
- ASTM E111 - 04(2010), *Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus*
- ASTM E132 - 04(2010), *Standard Test Method for Poisson's Ratio at Room Temperature*
- ASTM E146 - 83, *Methods of Chemical Analysis of Zirconium and Zirconium Alloys (Silicon, Hydrogen, and Copper)*
- ASTM E384 – 16, *Standard Test Method for Microindentation Hardness of Materials*
- ASTM E517 - 00(2010), *Standard Test Method for Plastic Strain Ratio r for Sheet Metal*
- ASTM E646 – 16, *Standard Test Method for Tensile Strain-Hardening Exponents (n -Values) of Metallic Sheet Materials*
- WK47776, *New Test Methods for Hydrogen Determination in Steel, Iron, Nickel and Cobalt Alloys by Inert Gas Fusion and Hot Extraction*

4.2 REGULATORY REQUIREMENTS

Fuel transportation will be in accordance with the provisions of 10 CFR Part 71, *Packaging and Transportation of Radioactive Material* and U.S. Department of Transportation rules in 49 CFR Part 173, *Shippers--General Requirements for Shipments and Packaging*. Transportation will also be subject to requirements of DOE Directive DOE M 460.2-1.

DOE orders that may have relevance to some of the detailed activities coordinated within this test plan, and hence should be reviewed for applicability, include:

- DOE G 421.1-1, *DOE Good Practices Guide Criticality Safety Good Practices Program Guide for DOE Nonreactor Nuclear Facilities*
- DOE O 435.1 Chg 1, *Radioactive Waste Management*
- DOE M 460.2-1, *Radioactive Material Transportation Practices*
- DOE O 5660.1, *Management of Nuclear Materials*

4.3 LEVEL OF ACCURACY, PRECISION, AND REPRESENTATIVENESS OF RESULTS

The accuracy, precision, and representativeness of the testing and analysis work performed are assessed as part of the uncertainty analyses for each of the products developed. The accuracy of the testing results is to be controlled by using appropriate instrument calibrations and reference standards. The precision of individual measurements is to be assessed based on use of replicate measurements and/or the established precision of the measuring and testing equipment used. Test results will be documented in the technical products.

4.4 OTHER REQUIREMENTS

A critical aspect to performing this type of work is providing a quality assurance program that gives confidence to the sponsor that the data derived from the examinations will be useful for any intended purposes, including regulatory review. The FCT quality assurance plan [8] and laboratory-specific procedures will be used to govern the work performed in this plan. The quality assurance program has two distinct but related aspects:

1) Assurance of quality in operations in all matters relating to safety in the work place and safety, public health protection, and environmental management in operations involving radiological, nuclear, and hazardous materials and equipment and
2) Assurance of quality both in special items production activities and in R&D data collection, data generation, analysis, use of software, documentation, and archiving of test samples.

The quality assurance program for operations in nuclear and radiological facilities must also comply with the provisions of other guidance documents such as:

- 10 CFR Part 830, Subpart A, *Nuclear Safety Management: Quality Assurance Requirements*
- DOE O 414.1A *Quality Assurance*
- DOE G 414.1-2 *Quality Assurance Management System Guide for use with 10 CFR 830.120 and DOE O 414.1*

The quality assurance programs for nuclear energy research, development and production activities are tailored to meet sponsor requirements.

5. EQUIPMENT

Measuring and test equipment necessary to conduct the examinations is controlled and calibrated at the facilities performing the work in accordance with approved laboratory procedures.

Major laboratory equipment necessary to conduct the work includes:

- hot cells
- gloveboxes
- ADEPT and associated examination equipment
- CIRFT
- SEM
- TEM
- SNTT system
- tensile testing machine and fixtures

Additional equipment that will need to be designed or procured includes the following: a full-length rod heat treatment system and an aerosolized radionuclide particle collection system.

6. DATA AND DOCUMENTATION

Observations, photographs, videotapes, digital files, and other data will be recorded on the appropriate medium and documented in laboratory notebooks as the examinations proceed. Progress of the PIE effort will be described in monthly project reports and informal e-mails. Consolidated status reports will be prepared annually. The final results of each major examination phase will be documented in a series of formal annual reports.

The raw data and data analysis algorithms will be made available to program participants. Most of this information will consist of computer files readable by commonly available programs such as Microsoft Excel and Word. Finished reports will be made available in PDF format. Copies of all records including documentation of equipment calibration and validation of software will be stored electronically at curie.ornl.gov.

7. QUALITY VERIFICATIONS

Detailed procedures for the PIE work will be available or written prior to the performance of the subtask and will be approved before use. All procedures used for the various testing will be retained for review and use when the corresponding sister rods from the RPC are extracted and examined for changes relative to the baseline properties. It is essential that the testing be performed identically prior to loading and after loading.

Specific hold points have been identified:

- At the completion of the NDE and prior to further characterization and testing, the data will be examined to determine if additional NDEs are necessary.
- A draft rod-segmenting plan has been developed that specifies the location of the desired specimens and their disposition. At the completion of Phase I, results from the NDEs will be evaluated against the draft segmenting plan and confirmed or modified prior to the beginning of the destructive PIE work. The revised segmenting plan will be issued with a revision to this test plan document.

8. REFERENCES

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APPENDIX A. DRAFT ROD CUT PLANS

Where available, the draft cutting plans are based on available gamma scans for the sister rod. Where the gamma scan has not yet been completed, preliminary cutting plans are based on available scans for rods from the same assembly or on representative burnup profiles for a 17×17 fuel assembly design at high burnups [A.1] as illustrated in Figure A-1. All cutting plans will be revisited at the end of the nondestructive examination and revised as needed.

White space shown in the cutting plan is reserved material. Only the primary baseline and fuel-rod heat-treatment rods have been mapped for cutting at this time, as the tests to be performed on the reserved rods have not yet been specified.

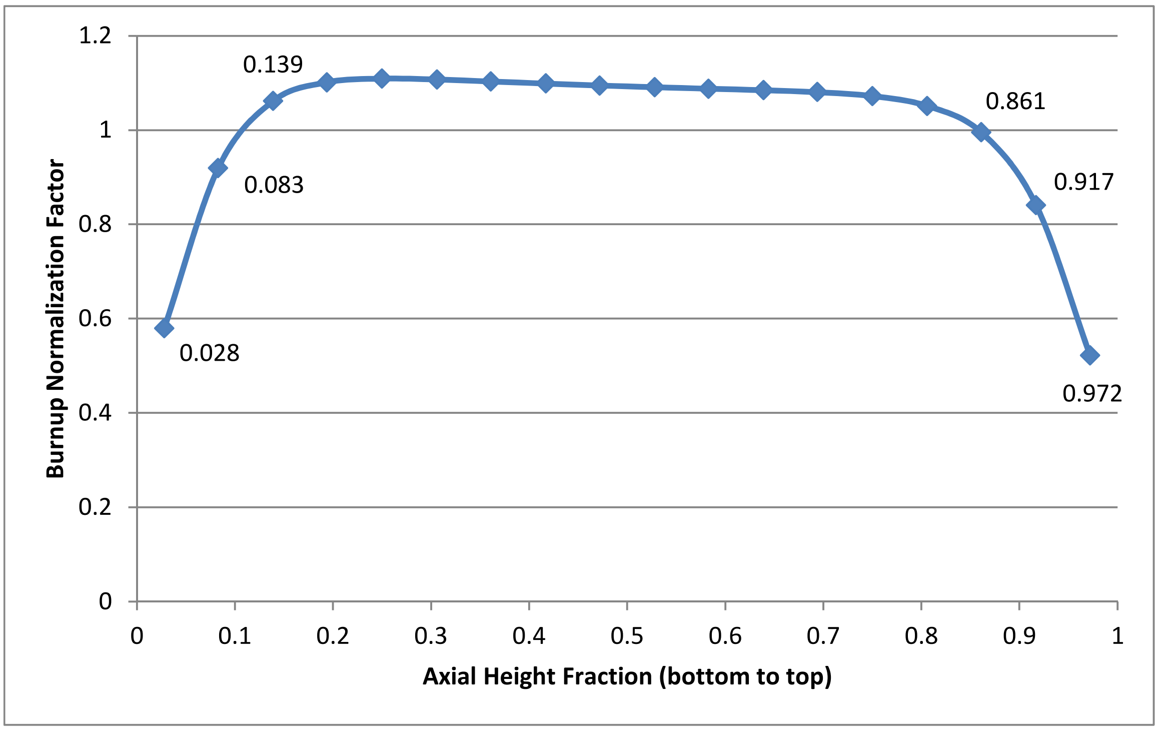

Figure A-1. Representative axial burnup profile for high burnup spent nuclear fuel rod.

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A.1. Caciapouti, R. J., and S. Van Volkinburg, *Axial Burnup Profile Database for Pressurized Water Reactors,* YAEC-1937, Yankee Atomic Electric Company, May 1997.

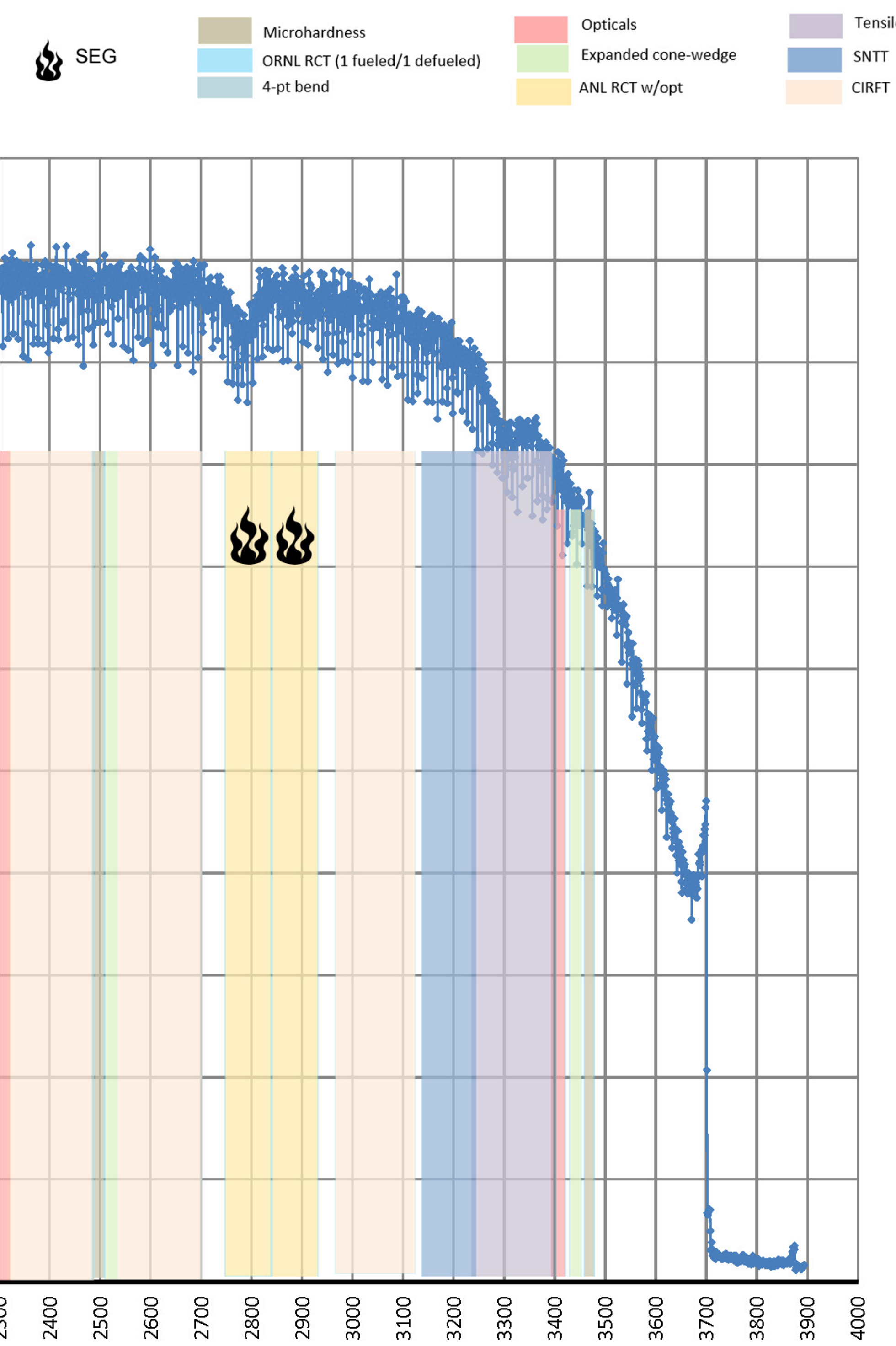


Figure A-2. 6U3I07 cutting plan.

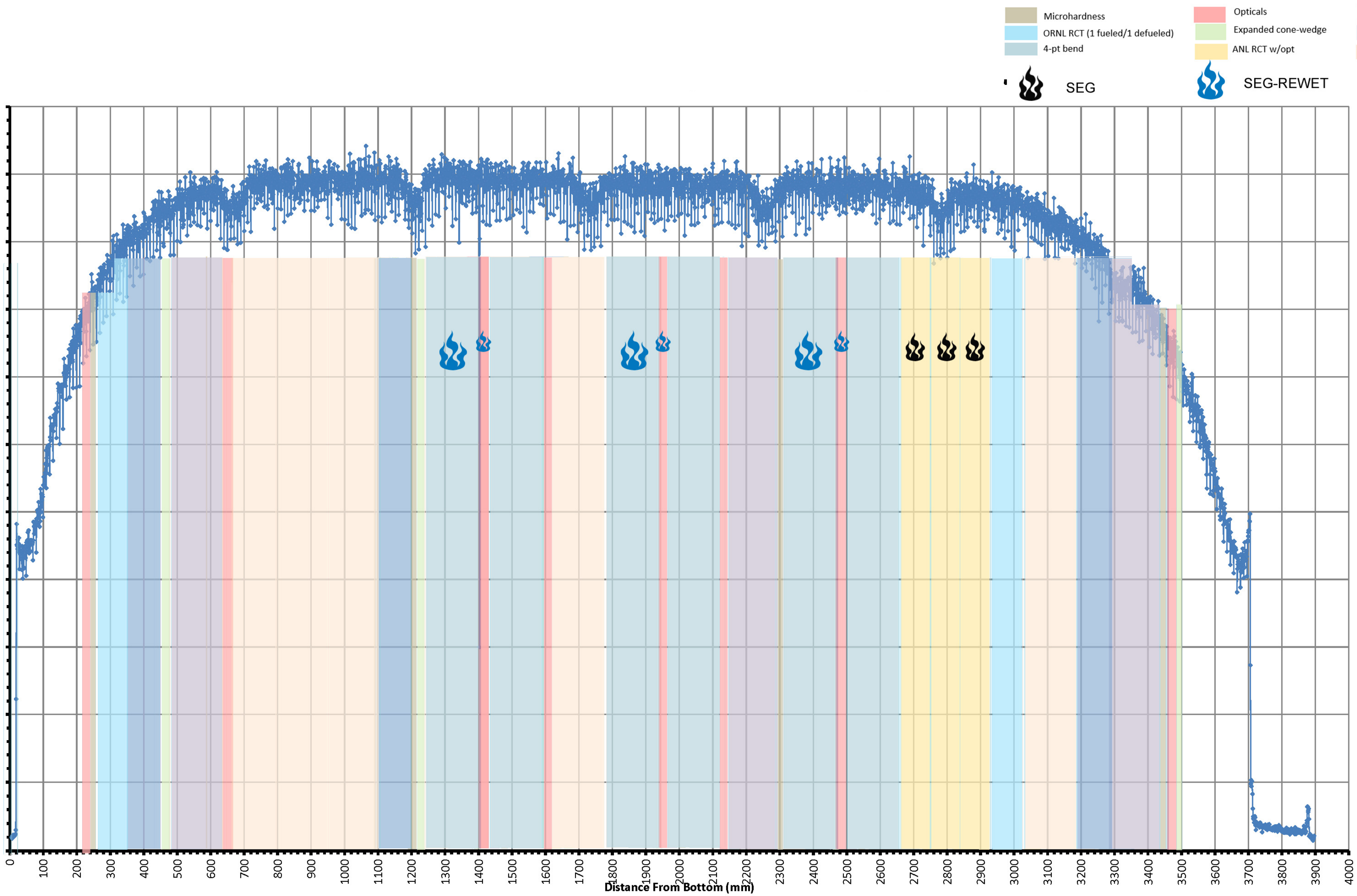


Figure A-3. 3D8E14 cutting plan.

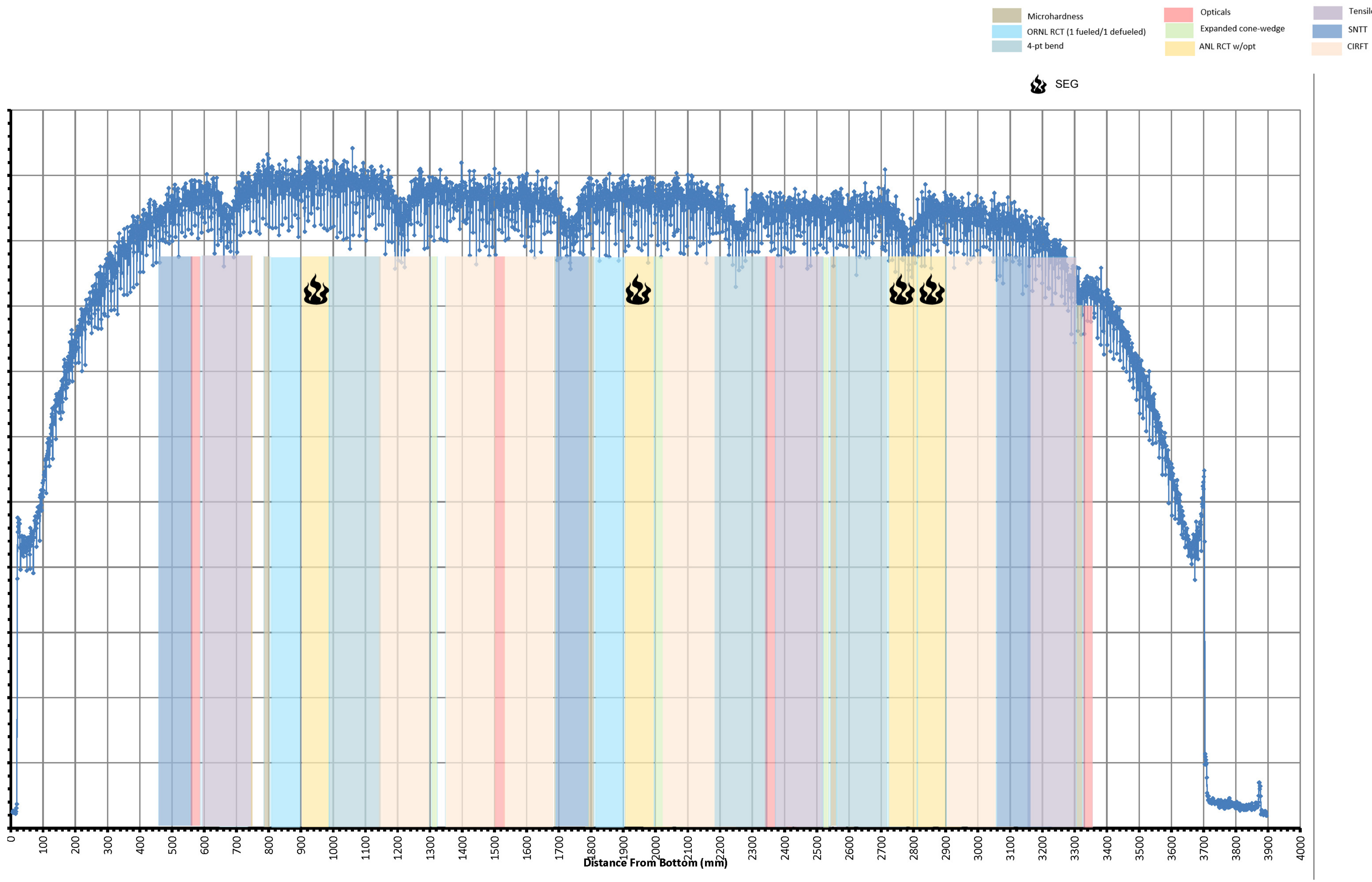


Figure A-4. 3D8B02 cutting plan.

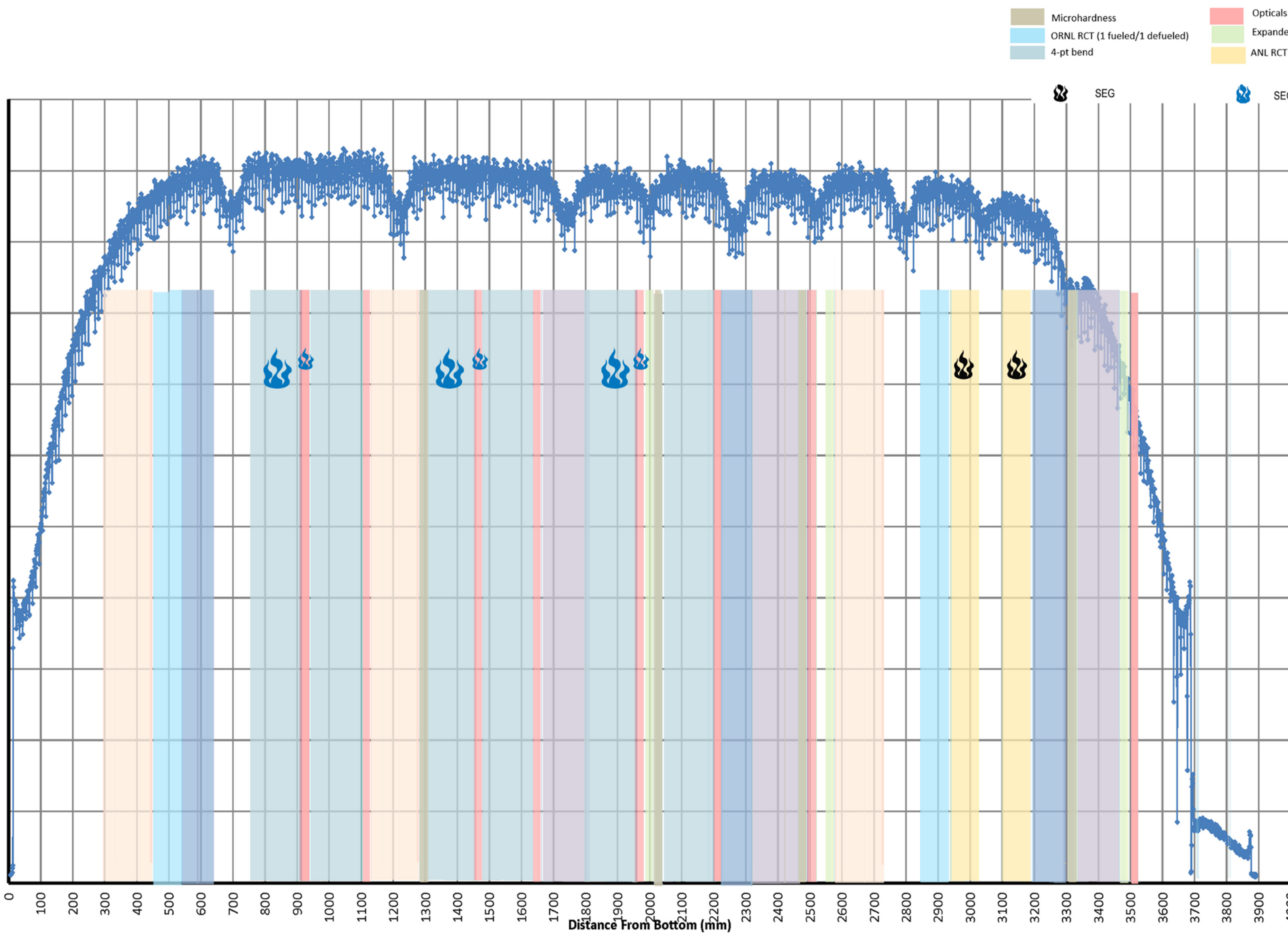


Figure A-5. 30AD05 cutting plan.

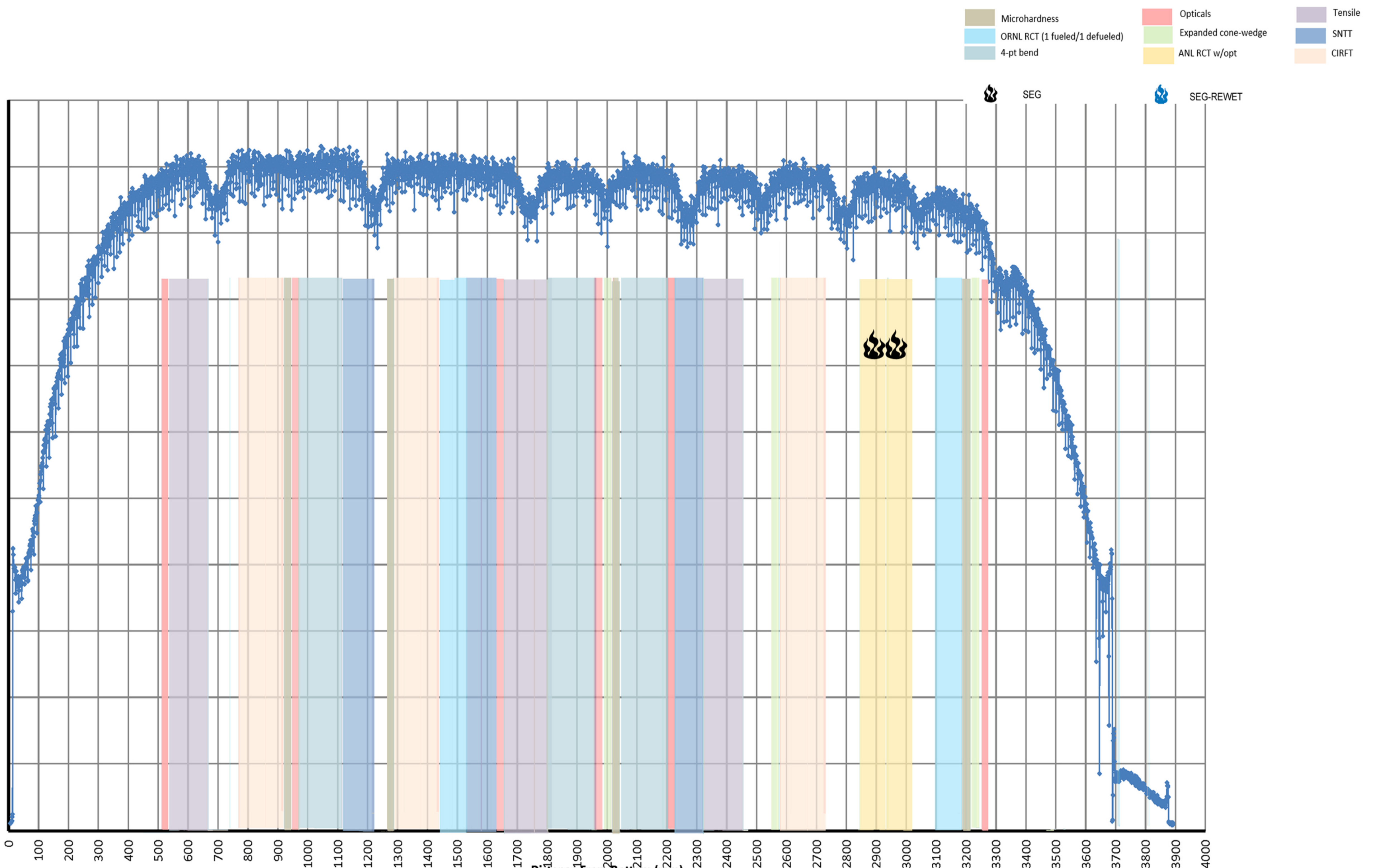


Figure A-6. 30AE14 cutting plan.

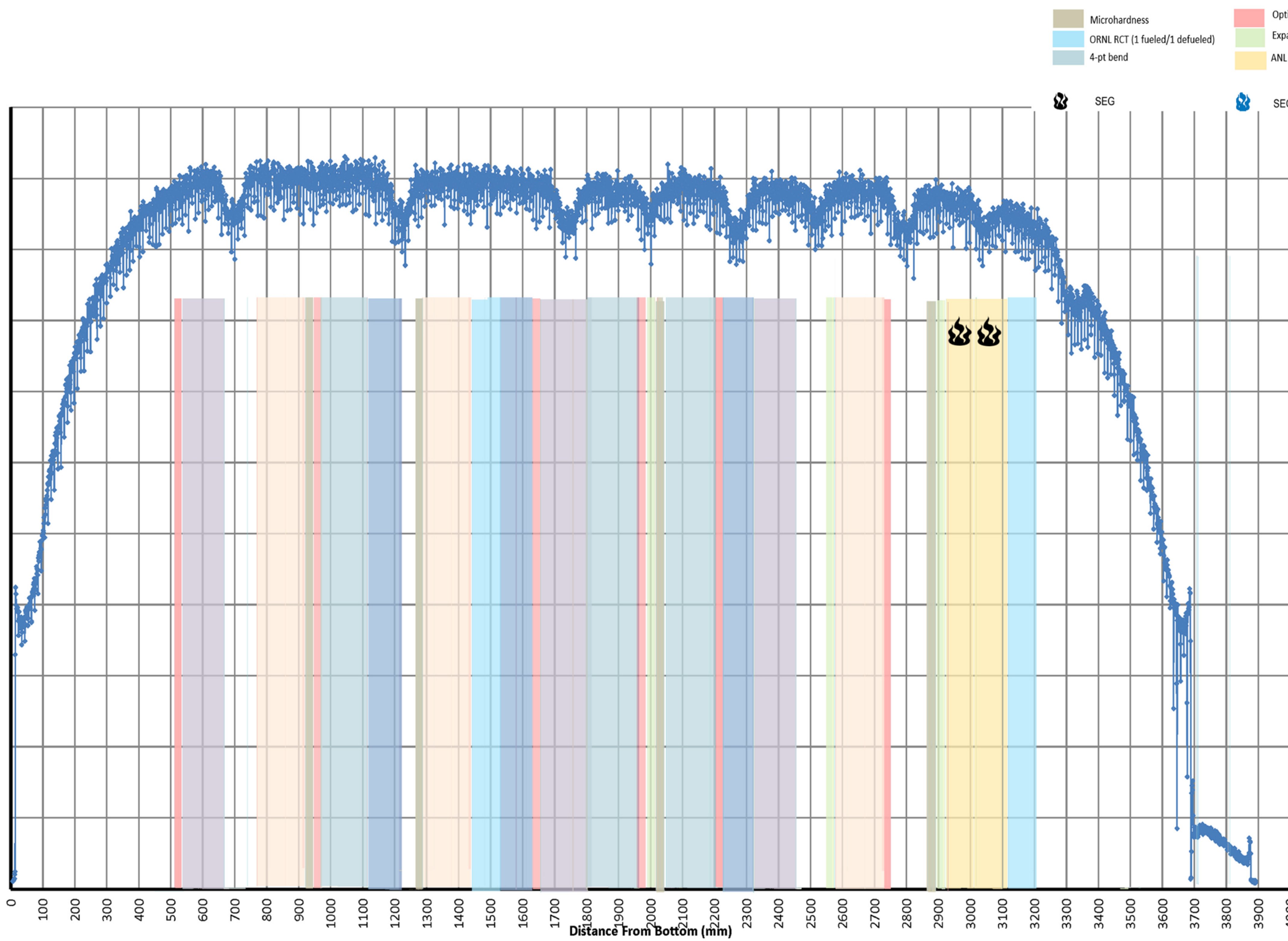


Figure A-7. 5K7O14 cutting plan.

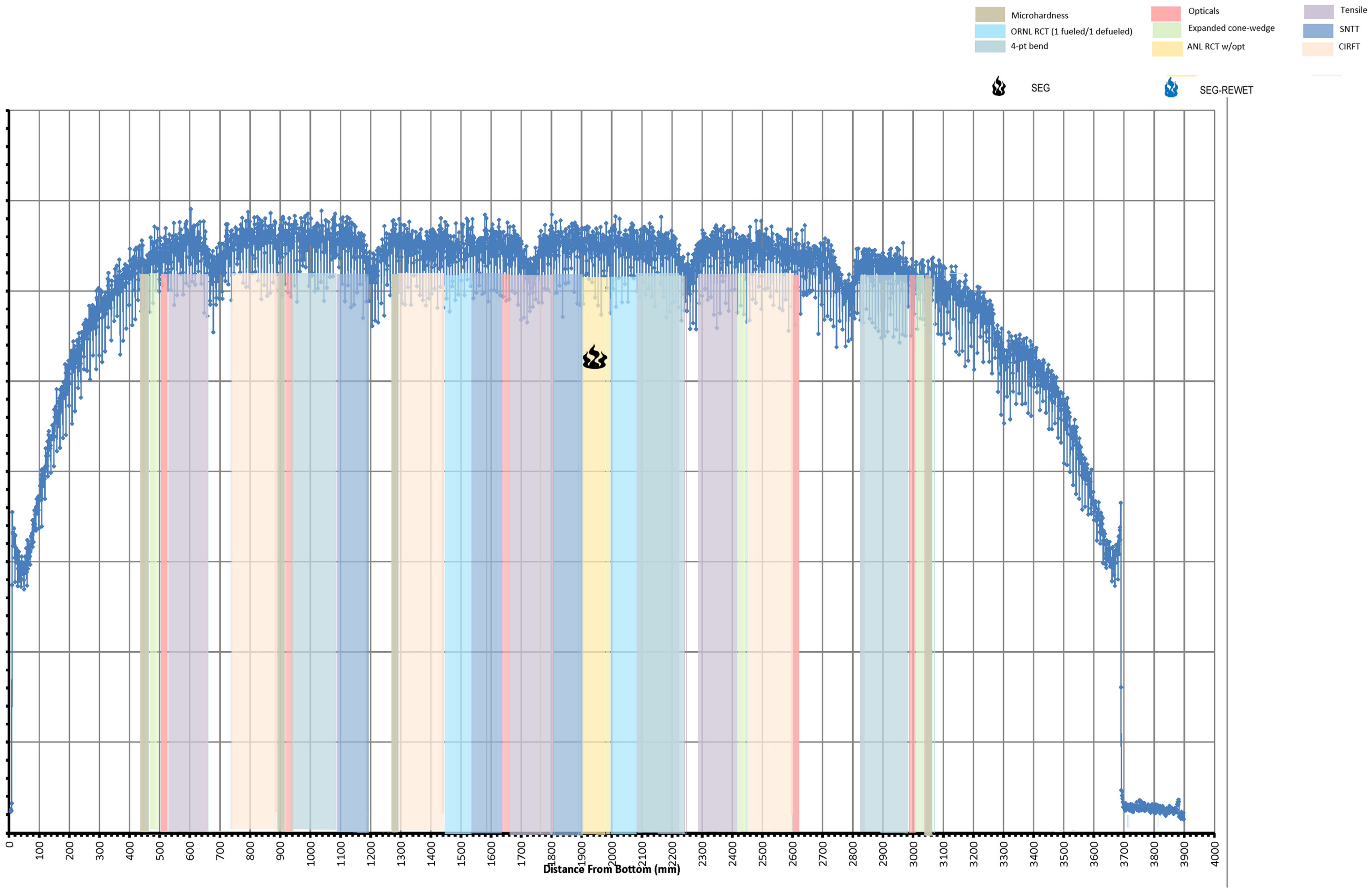


Figure A-8. 3A1B16 cutting plan.

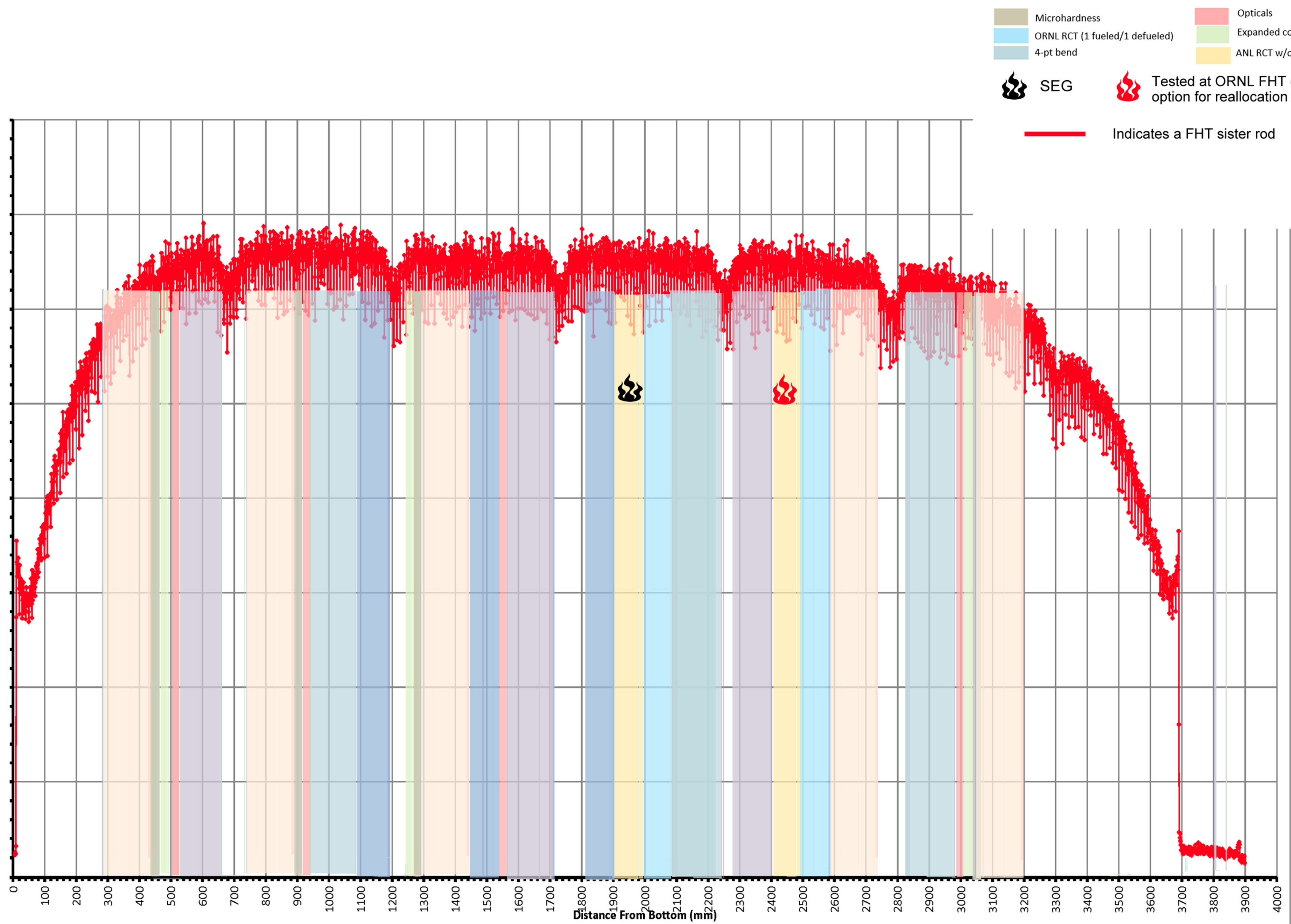


Figure A-9. F35P17 cutting plan.

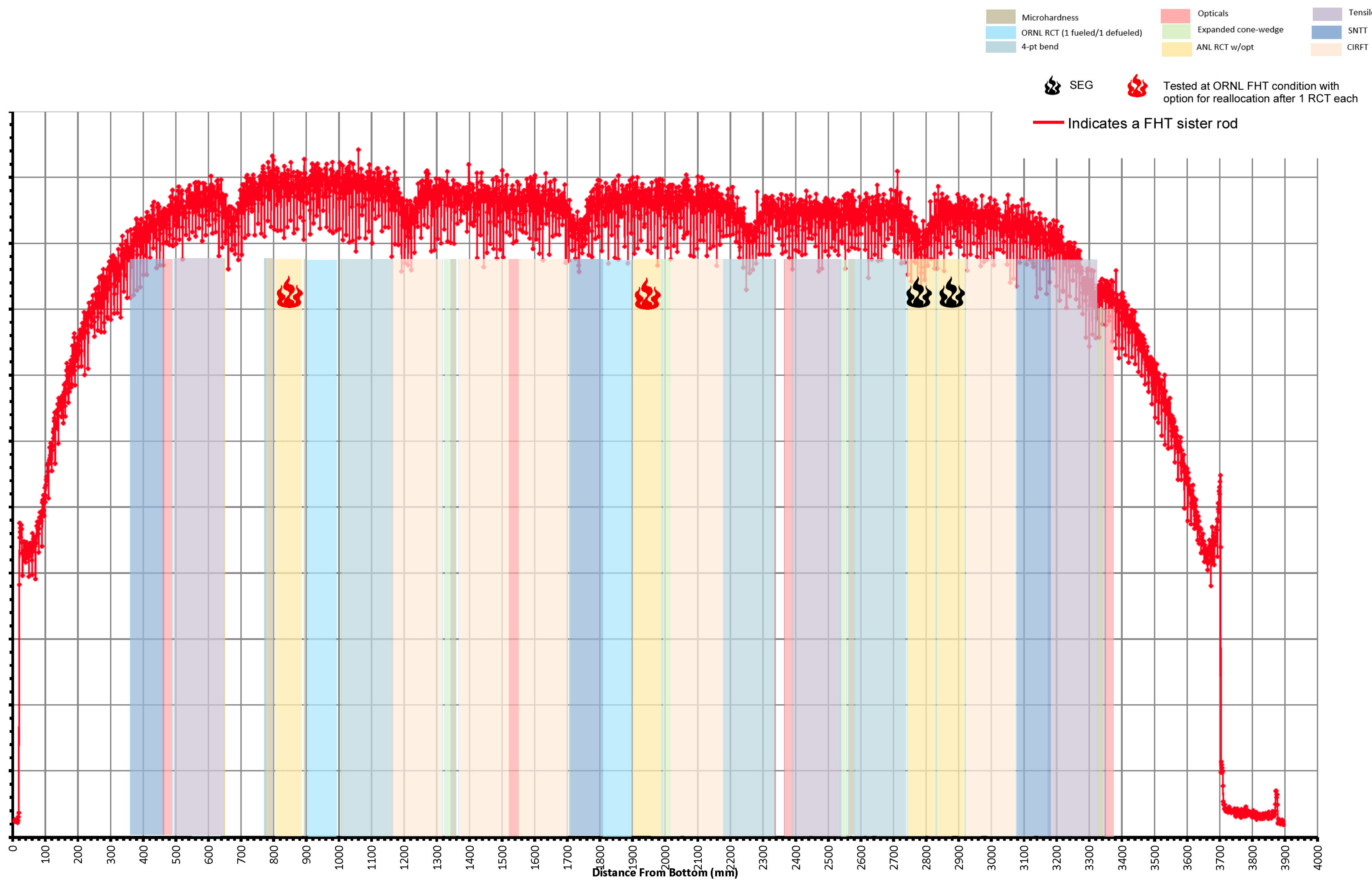


Figure A-10. 6U3M09 cutting plan.

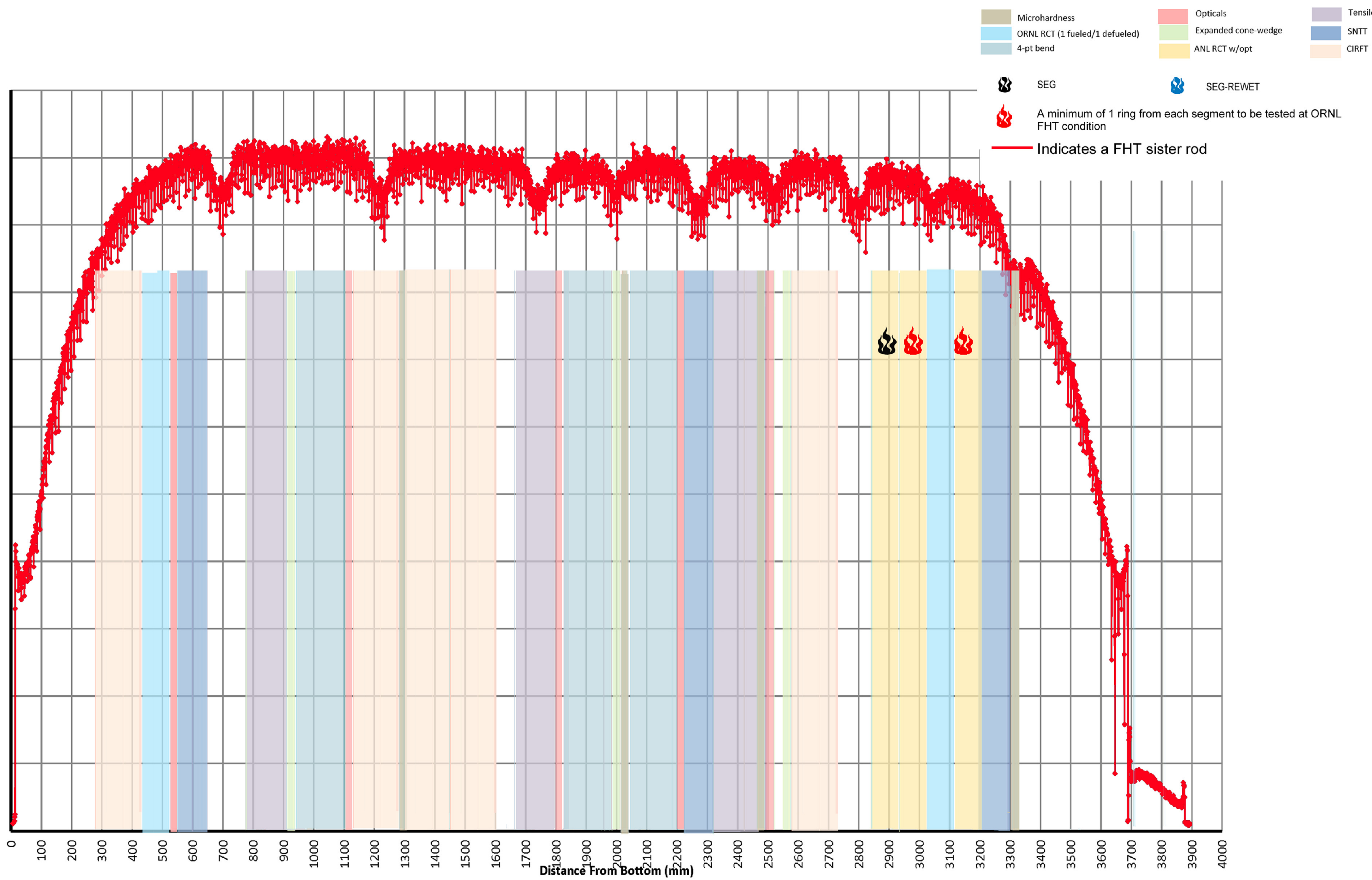
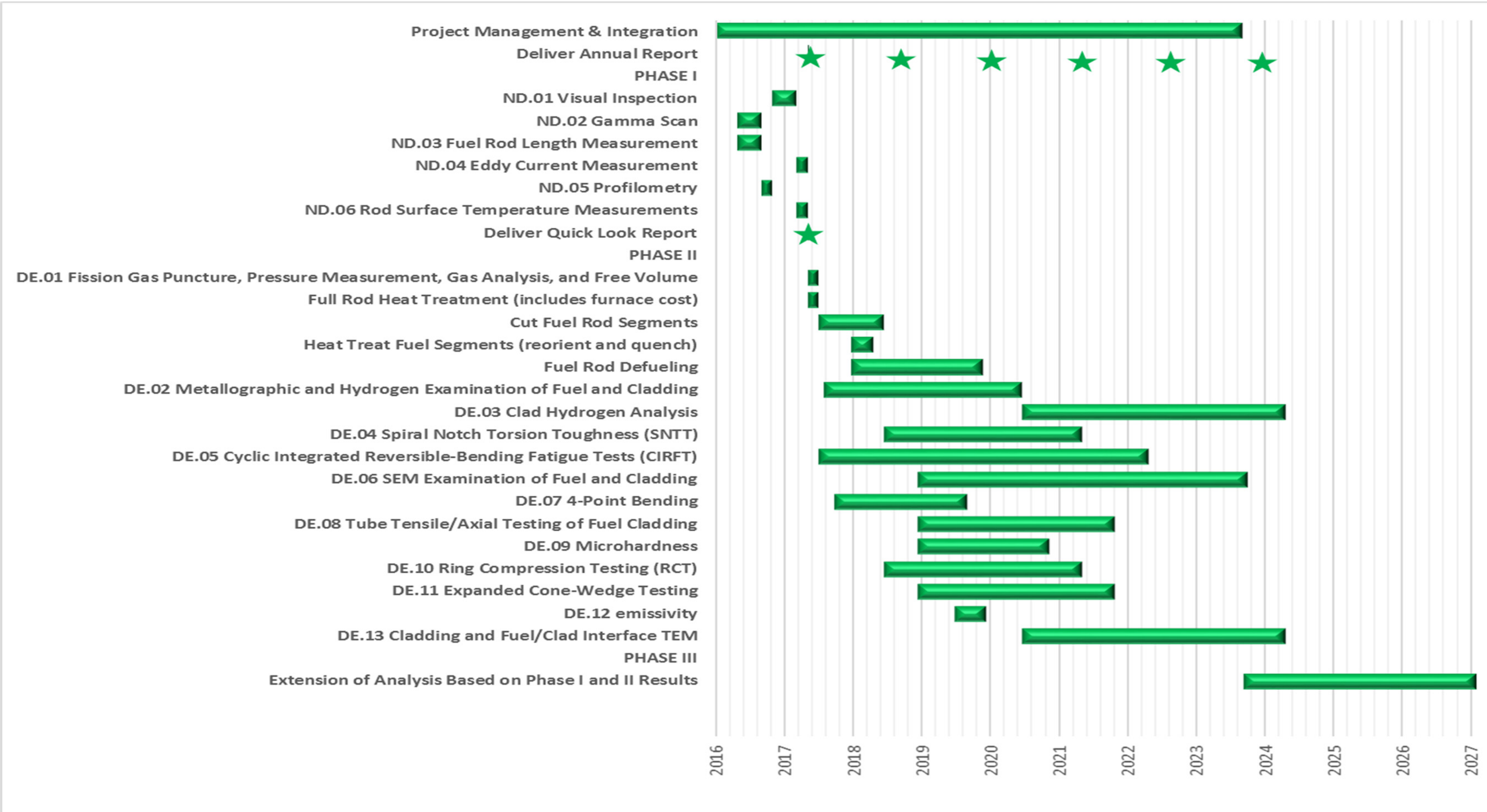


Figure A-11. 30AG09 cutting plan.

APPENDIX B. EXAMINATION SCHEDULE



* Note that the dates are contingent on the provision of adequate funding and do not include development/procurement time (as required) for test equipment. Additional time may also be required for hot cell implementation.

APPENDIX C. PROJECT BUDGET

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	Grand Total
Project Management & Integration	Project Management & Integration		$ 600,000	$ 405,600	$ 405,600	$ 407,160	$ 408,720	$ 407,160	$ 407,160	$ 332,280	$ -	$ -	$ -	$ -	$ 3,373,679
	Deliver Quick Look Report		$ 135,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 135,000
	Prepare hot cells, receive Sister Rods, Refurbish ADEPT	$ 825,000		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Equipment development, repair, and replacement		$ 40,000	$ 51,797	$ 51,797	$ 51,996	$ 52,195	$ 51,996	$ 51,996	$ 32,672	$ -	$ -	$ -	$ -	$ 384,449
	Deliver Annual Report		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Project Management		$ 825,000	$ 775,000	$ 457,397	$ 457,397	$ 459,156	$ 460,915	$ 459,156	$ 459,156	$ 364,952	$ -	$ -	$ -	$ -	$ 3,893,129
Phase 1 (NDE)	NDE Hot Cell Facility		$ 510,000		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 510,000
	NDE Hot cell experimentalists / staff		$ 765,000		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 765,000
	ND.01 Visual Inspection		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	ND.02 Gamma Scan		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	ND.03 Fuel Rod Length Measurement		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	ND.04 Eddy Current Measurement		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	ND.05 Profilometry		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	ND.06 Rod Surface Temperature Measurements		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
														$ -	$ -
Phase I: Non-Destructive Examination Total		$ -	$ 1,275,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,275,000
Phase II: Destructive PIE	DE Hot cell experimentalists / staff		$ -	$ -	$ 498,576	$ 500,494	$ 502,411	$ 500,494	$ 500,494	$ 182,172	$ -	$ -	$ -	$ -	$ 2,684,640
	DE Hot cell facility			$ -	$ 382,949	$ 382,949	$ 384,422	$ 385,895	$ 384,422	$ 384,422	$ 139,924	$ -	$ -	$ -	$ 2,444,981
	Full Rod Heat Treatment (includes furnace cost)			$ 416,840	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 416,840
	Heat Treat Fuel Segments (reorient and quench)			$ -	$ 538,333	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 538,333
	DE.01 Fission Gas Puncture, Pressure Measurement, Gas Analysis, and Free Volume		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Cut Fuel Rod Segments		$ -	$ 184,167	$ 92,083	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 276,250
	Fuel Rod Defueling		$ -	$ 824,500	$ 412,250	$ 12,750	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,249,500
	DE.02 Metallographic and Hydrogen Examination of Fuel and Cladding		$ -	$ 66,300	$ 179,563	$ 180,253	$ 37,984	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 464,100
	DE.06 SEM Examination of Fuel and Cladding		$ -	$ -	$ 5,993	$ 27,934	$ 28,041	$ 27,934	$ 27,934	$ 12,415	$ -	$ -	$ -	$ -	$ 130,250
	DE.13 Cladding and Fuel/Clad Interface TEM		$ -	$ -	$ -	$ -	$ 2,985	$ 7,869	$ 7,869	$ 7,839	$ 3,437	$ -	$ -	$ -	$ 30,000
	Optical Inspections Total		$ -	$ 66,300	$ 185,556	$ 208,187	$ 69,010	$ 35,803	$ 35,803	$ 20,254	$ 3,437	$ -	$ -	$ -	$ 624,350
	DE.03 Clad Hydrogen Analysis		$ -	$ -	$ -	$ -	$ 35,190	$ 44,370	$ 44,370	$ 44,200	$ 35,870	$ -	$ -	$ -	$ 204,000
	DE.04 Spiral Notch Torsion Toughness (SNTT)		$ -	$ 77,350	$ 306,000	$ 221,850	$ 210,800	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 816,000
	DE.05 Cyclic Integrated Reversible-Bending Fatigue Tests (CIRFT)		$ 150,000	$ 90,667	$ 245,556	$ 246,500	$ 247,444	$ 246,500	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,226,667
	DE.07 4-Point Bending		$ -	$ 34,000	$ 61,861	$ 108,139	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 204,000
	DE.08 Tube Tensile/Axial Testing of Fuel Cladding		$ -	$ -	$ 153,000	$ 369,750	$ 89,250	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 612,000
	DE.09 Microhardness		$ -	$ -	$ 550,366	$ 568,020	$ 217,421								$ 1,335,808
	DE.10 Ring Compression Testing (RCT)		$ -	$ 351,000	$ 550,366	$ 568,020	$ 217,421		$ -	$ -	$ -	$ -	$ -	$ -	$ 1,686,808
	DE.11 Expanded Cone-Wedge Testing		$ -	$ 171,000	$ 69,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 240,000
	DE.12 emissivity		$ -	$ -	$ -	$ 49,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 49,000
Phase II: Destructive PIE Total			$ 150,000	$ 2,215,824	$ 4,045,897	$ 3,235,659	$ 1,973,370	$ 1,213,061	$ 965,088	$ 631,048	$ 179,231	$ -	$ -	$ -	$ 14,560,177
Phase III: Extension of Analysis Based on Phase I and II Results		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,260,551	$ 1,575,689	$ 2,100,918	$ 2,359,774	$ 2,414,022	$ 9,710,954
Phase III: Extension of Analysis Based on Phase I and II Results			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -		$ -
		$ 825,000	**$ 2,200,000**	**$ 2,673,220**	**$ 4,503,294**	**$ 3,694,815**	**$ 2,434,285**	**$ 1,672,217**	**$ 1,424,244**	**$ 2,256,551**	**$ 1,754,920**	**$ 2,100,918**	**$ 2,359,774**	**$ 2,414,022**	**$ 29,488,260**

APPENDIX D. PROJECT MILESTONE LISTING

Milestone Description (not necessarily in order; see the schedule in Appendix B for timing of the milestones)
Phase I
Preliminary NDE imaging
Final rod segmenting plan
Comprehensive NDE report
Phase II
Complete design and installation of full rod heat treatment capability
Complete qualification of segment heat treatment method
Complete demonstration of heat treatment methods/capabilities using dummy materials
Develop and design aerosolized radionuclide collection system from clad breach
Complete rod puncturing selected rods
Rod segmentation (selected rods)
Segment defueling (selected segments)
Shipments to PNNL and ANL: complete readiness assessments and approval process for shipping and receiving materials
Shipments to PNNL and ANL: complete rod segmenting
Shipments to PNNL and ANL: obtain shipping containers and prepare shipping paperwork
Shipments to PNNL and ANL: pack segments; ship
Document final examination procedures
Establish temperature profiles for application to FHT and SEG/SEG-REWET specimens
Apply heat treatment to selected full length rods (FHT)
Apply heat treatment to selected segments [SEG/SEG-REWET]
Begin mechanical DE
Begin optical DE
Deliver final comprehensive DE report
Prepare Phase III test plan and update rod segmenting plans
Phase III
TBD
Phase IV
Project management activities
Annual status reports

APPENDIX II. HIGH BURNUP SPENT FUEL DATA PROJECT PNNL SISTER ROD TEST PLAN

HIGH BURNUP SPENT FUEL DATA PROJECT

PNNL SISTER ROD TEST PLAN

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology
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February 28, 2017
SFWD-SFWST-2017-000032
National Laboratory Report No. XXXXXX

SUMMARY

This report fulfils the requirements for milestone M3SF-17PN010201035 "PNNL Sister Rod Test Plan."

As part of the High Burnup Spent Fuel Data Project sponsored by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI), 25 sister rods have been sent to Oak Ridge National Laboratory (ORNL) for nondestructive examination (NDE). Once the NDE is complete, the rods will be punctured and the end-of-life rod internal pressure and rod free volume measured. 10 of the sister rods, four M5® cladded, five ZIRLO® cladded, and one Zircaloy-4 cladded, will be sent to Pacific Northwest National Laboratory (PNNL) for destructive testing.

The baseline (i.e., post-irradiation and pool storage, but before dry storage) or t0 (time zero) characteristics and material properties of cladding are well known by the fuel vendors. These t0 properties are used in fuel performance codes. However, all commercial SNF in dry storage or to be transported will have been dried using either vacuum drying or a forced gas dehydration process. During drying, the temperature of the cladding increases. If the temperature and corresponding hoop stress are sufficiently high, hydrides within the cladding may dissolve and, upon cooling, precipitate in the radial direction. It is therefore necessary to obtain the characteristics and material properties of the cladding after it has undergone the drying and cask helium backfill processes, or the t0'(time zero prime) condition, for use in understanding and modeling cladding performance for extended storage and transportation.

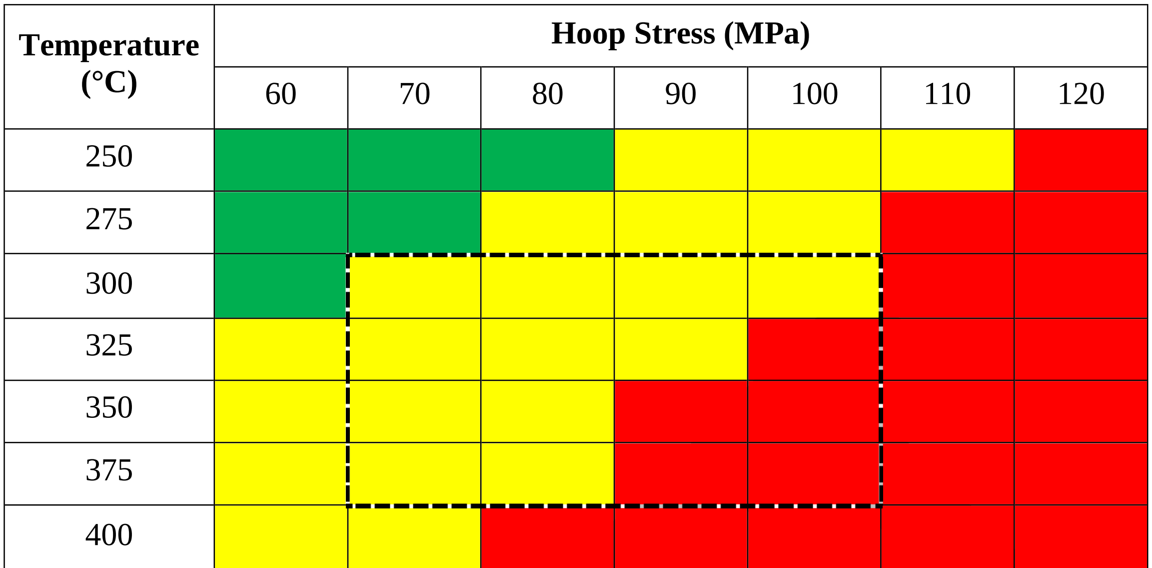
The objectives of the PNNL sister rod testing are to:

- Determine the conditions under which radial hydrides form and, more importantly, under which sufficient radial hydrides form to affect material properties and cladding performance (i.e., determine when t0' properties are significantly different from t0 properties). Testing segments of the sister rods at temperatures and hoop stresses greater than those expected in the Research Project Cask will expand the applicability of the High Burnup Spent Fuel Data Project to encompass the conditions expected for realistic cask loading across the U.S. nuclear industry.
- Determine material properties under t0' conditions for use in modeling and analyses for cladding performance during extended storage, including cask tip-over, drop, and seismic events, as well as for normal conditions of transport (NCT).

The data obtained under this test plan, combined with the data from testing performed on sister rods at ORNL and the data from the Research Project Cask, will be used to close the Cladding H_2 Effects: Embrittlement and Reorientation data gap for standard rods from pressurized water reactors (PWRs). Standard rods do not include integral fuel burnable absorber (IFBA) rods that may have a significantly higher EOL RIP and thus higher hoop stress. Additional analyses will be performed to determine if testing on IFBA rods or boiling water reactor (BWR) rods will be necessary.

As discussed in the *High Burnup Spent Fuel Data Project-Sister Rod Test Plan Overview* and expanded on in this document, the peak cladding temperature (PCT) for systems analyzed to date range from only 271°C to 325°C, much lower than the regulatory guidance limit of 400°C. Most cladding in any given system is well below the PCT for that system. Similarly, realistic calculations for hoop stress, especially at these lower temperatures, are in the range of 60 MPa to 80 MPA for standard PWR rods.

The first priority will be to perform radial hydride treatment (RHT) at various temperature and hoop stress combinations to determine the threshold for formation of radial hydrides and for shifting the ductile-to-brittle transition temperature (DBTT) above 50°C as determined from ring compression tests (RCTs). The threshold is expected to be a function of alloy type; hydride concentration, distribution, and orientation; peak hoop stress; PCT; and temperature and stress histories. RHT on defueled cladding segments will be performed at PNNL. Samples will then be sent to Argonne National Laboratory (ANL) for RCT. The combined results will be used to fill in the matrix in Figure S1.



Green represents minimal hydride reorientation; Yellow represents obvious hydride reorientation but DBTT<50°C; Red represents significant hydride reorientation and DBTT≥50°C. Representative only.

Figure S1. Representative RHT Test Matrix.

The second objective is to determine the material properties of post-dried, or t0', cladding for use in models to predict cladding performance during extended storage and transportation. Properties such as yield strength, ultimate tensile strength, work hardening rate, and uniform plastic elongation will be determined using axial tube tensile tests. Tube compression tests will be performed and used to determine if the yield strength, yield point, Young's modulus, and compressive strength are different from the tensile properties for samples subjected to identical RHT. Biaxial stress, ultimate hoop strength, and percent total circumferential elongation are some of the properties that will be determined using tube burst tests. Axial tube tensile tests, tube compression tests, and tube burst tests will all be performed in accordance with approved ASTM International standards.

The test matrix for the material properties tests is complex and heavily dependent on the results of the RHT and RCT tests as well as the initial material property tests. A test matrix for one ZIRLO® rod is proposed. Follow on tests of the other rods to examine the effects of different RHT, higher test temperatures, varying strain rates, variable burnup and total hydrogen content, etc. will be performed only after detailed analysis of the results from the first rod and discussion with the DOE team and external experts.

ACKNOWLEDGEMENTS

The authors wish to acknowledge and thank Mike Billone (ANL) for his expert advice and input to this test plan. We thank Ned Larson (DOE Office of Nuclear Energy) and Ken Sorenson and Sylvia Saltzstein (Sandia National Laboratories) for their management of this program and their support. We thank the external reviewers from industry and the Nuclear Waste Technical Review Board for their comments and review.

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REVISION HISTORY

ACRONYMS

ANL	Argonne National Laboratory
ASTM	ASTM International
BWR	boiling water reactor
CIRFT	cyclic integrated reversible bending test
CSR	contractile strain ratio
DBTT	ductile to brittle transition temperature
DIC	digital image correlation
DOE	U.S. Department of Energy
DSC	dry storage cask
EI	effective flexural rigidity
EOL RIP	end of life rod internal pressure
EPRI	Electric Power Research Institute
GWd	gigawatt-days
HBU	high burnup
HLRF	High Level Radiochemistry Facility
IFBA	integral fuel burnable absorber
ISFSI	independent spent fuel storage installation
Low-tin	low-Sn
MCT	minimum cladding temperature
MPa	megapascal
MPC	multipurpose canister
MTU	metric tons of uranium
NCT	normal conditions for transport
NDE	non-destructive examinations
NRC	U.S. Nuclear Regulatory Commission
OD	outer diameter
ORNL	Oak Ridge National Laboratory
PCT	peak cladding temperature
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
PWR	pressurized water reactor
RCT	ring compression testing
RHT	radial hydride treatment

RPL	Radiochemical Processing Laboratory
SAL	Shielded Analytic Laboratory
SNF	spent nuclear fuel
t0	time zero
t0’	time zero prime
UNF-ST&DARDS	Used Nuclear Fuel – Storage, Transportation & Disposal Analysis Resource and Data Systems
Zr-4	Zircaloy-4
wppm	weight parts per million

REGISTRATIONS AND TRADEMARKS

M5®	Trademark of AREVA NP registered in the United States and in other countries.
ZIRLO®	Registered trademark of Westinghouse Electric Company LLC in the United States and other countries.

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HIGH BURNUP SPENT FUEL DATA PROJECT: PNNL SISTER ROD TEST PLAN

1. INTRODUCTION

Under the High Burnup Spent Fuel Data Project sponsored by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI), a U.S. Nuclear Regulatory Commission (NRC) -licensed storage cask (an AREVA TN-32B) will be loaded with 32 high burnup (HBU) spent nuclear fuel (SNF) assemblies at Dominion's North Anna Nuclear Power Station in Mineral, Virginia (EPRI 2014). The cask, referred to as the Research Project Cask, will be stored at the North Anna Nuclear Power Station independent spent fuel storage installation (ISFSI), where temperatures will be monitored and gas samples taken. After a period of approximately 10 years, the cask will be transported to a facility to be opened, so that the SNF can be examined and tested to provide confirmation that HBU SNF can be stored safely and is transportable.

In parallel with the 10-year storage of HBU SNF in the Research Project Cask, 25 HBU fuel rods (Hanson et al. 2016), which have been removed either from assemblies going into the Research Project Cask or from assemblies with similar irradiation histories, will be characterized and tested. These 25 rods are referred to as "sister rods" to indicate that they have similar as-irradiated characteristics as the rods against which they will be compared in about 10 years. The *High Burnup Spent Fuel Data Project-Sister Rod Test Plan Overview* (Hanson et al. 2016), referred to hereafter as the *Overview*, provides the background and higher-level overview of the sister rod testing as well as descriptions of the sister rods and the assemblies from which they came. All non-destructive examinations (NDE), as well as the rod puncturing to measure end-of-life rod internal pressure (EOL RIP) as described by Montgomery et al. (2017), will be performed by Oak Ridge National Laboratory (ORNL) prior to designated rods being sent to Pacific Northwest National Laboratory (PNNL). This document provides the specific plan for the 10 sister rods to be tested at PNNL.

The baseline (i.e., post-irradiation and pool storage, but before dry storage) or t0 (time zero) characteristics and material properties of cladding are well known by the fuel vendors. The t0 material properties of Zircaloy-4 (Zr-4) and low-tin (low-Sn) Zr-4 are well known and publicly available. The publicly available t0 data for ZIRLO® and M5® are much more limited. These t0 properties are used in fuel performance codes (Geelhood et al. 2008, Geelhood et al. 2014).

However, all commercial SNF in dry storage or to be transported will have been dried using either vacuum drying or a forced gas dehydration process. During drying, the temperature of the cladding increases. If the temperature and corresponding hoop stress are sufficiently high, hydrides within the cladding may dissolve and, upon cooling, precipitate in the radial direction. Cladding may be more susceptible to failure under pinch loading if sufficient radial hydrides form (Billone et al., 2013a). It is therefore necessary to obtain the characteristics and material properties of the cladding after it has undergone the drying and cask helium backfill processes, or the t0'(time zero prime) condition, for use in understanding and modeling cladding performance for extended storage and transportation.

The objectives of the PNNL sister rod testing are to:

- Determine the conditions under which radial hydrides form and, more importantly, under which sufficient radial hydrides form to affect material properties and cladding performance (i.e., determine when t0' properties are significantly different from t0 properties). Hydride reorientation and mechanical properties are a function of alloy type and processing parameters (i.e., texture, cold work, and chemistry, especially oxygen and sulfur content); hydride concentration, distribution, and orientation; peak hoop stress; peak cladding temperature (PCT); and temperature and stress histories (e.g., cooling rate). Testing segments of the sister rods at temperatures and hoop stresses greater than those expected in the Research Project Cask will expand the applicability of the High Burnup Spent Fuel Data Project to encompass the conditions expected for realistic cask loading across the U.S. nuclear industry.

- Determine material properties under t0' conditions for use in modeling and analyses for cladding performance during extended storage, including cask tip-over, drop, and seismic events, as well as for normal conditions of transport (NCT).

The data obtained under this test plan, combined with the data from testing performed on sister rods at ORNL (Montgomery et al. 2017) and the data from the Research Project Cask, will be used to close the Cladding H_2 Effects: Embrittlement and Reorientation data gap (Hanson et al. 2012) for standard rods from pressurized water reactors (PWRs). Standard rods do not include integral fuel burnable absorber (IFBA) rods that may have a significantly higher EOL RIP and thus higher hoop stress. Additional analyses will be performed to determine if testing on IFBA rods or boiling water reactor (BWR) rods will be necessary.

This test plan will further refine the range of parameters for the test matrix as discussed in the *Overview* (Hanson et al. 2016), delineate the data necessary for modeling the fuel performance during extended storage and NCT, and outline the testing methodology for meeting the two testing objectives.

1.1 Test Matrix Parameters

In addition to temperature and hoop stress as discussed in the *Overview* (Hanson et al. 2016), hydride reorientation is dependent on the initial hydride concentration, distribution, and orientation. Billone and Burtseva (2016) have shown that M5® is especially sensitive to an increase in hydrogen content from 58 wppm to 80 wppm when subjected to a 90-MPa peak stress.

1.1.1 Temperature

As detailed in the *Overview* (Hanson et al. 2016), the expected range of cladding temperatures may vary from approximately 140°C at the low ends of the fuel rods to as high as 400°C, the regulatory guidance limit established by the NRC in ISG-11, Rev. 3 (NRC 2003). Based on the PNNL thermal modeling of the Research Project Cask and accounting for expected decay heats, the cladding temperatures range from a low (minimum cladding temperature, MCT) of 138°C to a PCT of 271°C (Fort et al 2016a). PNNL performed a similar analysis on a MAGNASTOR system loaded at the Duke Catawba Nuclear Station. After correcting for the lower emissivity for the basket, the temperatures range from a MCT of 155°C to a PCT of 310°C (Fort et al. 2016b). The temperature profile for a canister-based system with internal convection is also markedly different from the profile for a cask system such as the Research Project Cask where radial conduction is dominant. In modern vertical canister systems, the PCT is near the top of the fuel whereas for bare-fuel cask systems and horizontal canister systems the PCT is near the fuel midpoint. Similar analyses performed by ORNL in the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) determined that the maximum PCT for the systems modeled to date is 325°C (Scaglione 2015).

It is reasonable to conclude that PCT will be below 350°C for all systems loaded to date since the implementation of the NRC regulatory guidance limit and for systems to be loaded in the future under similar guidance. In reality, the PCT for most systems will be below 325°C. In addition, as shown by the PNNL thermal analyses (Fort et al. 2016a, 2016b), only a small fraction of the cladding achieves the PCT, and the overwhelming majority is well below 300°C.

Just as important as the temperatures reached during drying are the temperatures at the time an event (e.g., a seismic event) occurs or when the fuel is transported. Table 1 summarizes the temperatures at various times from the thermal analysis of the MAGNSTOR cask (Fort et al. 2016b). Cladding is naturally more ductile at higher temperatures. Three important conclusions regarding temperature are:

- The vast majority of cladding will experience PCTs low enough that only minimal hydride reorientation may occur.
- Even if radial hydrides affect the material properties and response (e.g., by increasing the ductile-to-brittle transition temperature, DBTT), it is likely that the cladding temperature in the area that had high enough temperature for hydrides to reorient will be above the DBTT for at least 100 years even under the more extreme temperature and hoop stress conditions previously tested (Billone et al. 2013a, Billone and Burtseva 2016).
- Material properties measured at room temperature will be at the lower bound for ductility and on the upper bound on yield and ultimate tensile stress. Because of the large range of temperatures within a storage cask, and even along a single fuel rod, and because of the relatively large (~30%) change in cladding strength anticipated over this temperature range, it is important to have material properties determined at various temperatures.

Table 1. Cladding Temperatures as a Function of Time (Fort et al. 2016b).[1]

Time (yrs)	PCT (°C)	MCT (°C)
0 (drying)	310	155
10	257	136
50	167	98
100	120	75
200	90	60
300	79	55

(1) 9°C added to the values reported to account for lower emissivity of basket material

1.1.2 Hoop Stress

Hoop stress is a key contributor to the potential degradation phenomena of creep, delayed hydride cracking, and hydride reorientation. At the temperatures expected during drying, the peak hoop stress for most standard PWR cladding (i.e., excluding IFBA rods) will be in the 60 to 80 MPa range, depending on the oxide layer thickness values and the average gas temperatures within the rods during drying and early storage (Hanson et al. 2016, Billone and Burtseva 2016). Billone and Burtseva (2016) also found that the DBTT for ZIRLO® is highly sensitive to the hoop stress in the range 90±3 MPa.

Raynaud and Einziger (2015) recently performed an analysis of cladding stress during extended storage of HBU SNF. In their analysis, they assumed a burnup of 65 GWd/MTU for a typical 17×17 PWR cladding. They also assumed a PCT of 400°C. As reported in the *Overview* (Hanson et al. 2016), this burnup is significantly above the average burnups being discharged and still well above the highest burnup assemblies being discharged, with the exception of lead test assemblies. Similarly, the assumed temperature is well above the PCT, as discussed in Section 1.1.1. Reynaud and Einziger (2015) accounted for a realistic decay gas release, though from this higher burnup fuel and much higher temperatures, as well as cladding strain resulting from pellet swelling. Even then, the peak hoop stress was estimated to be 100 MPa and occurred at the beginning of storage before gas release during storage (as opposed to during irradiation) and pellet swelling would be significant contributors. Just applying the ideal gas law reduces this hoop stress to 93 MPa at 350°C, 89 MPa at 325°C, and 85 MPa at 300°C.

Even if it is assumed that all of the gas in the rod is at the PCT, the hoop stress is expected to be below 90 MPa. In the more likely scenario that there is at least some gas communication throughout the entire rod, then the average gas temperature would be much lower and the hoop stress would be below 80 MPa.

The EOL RIP will be measured at ORNL for each of the 25 sister rods (Montgomery et al. 2017). Combined with the oxide layer thickness measured on individual samples, the hoop stress for each sister rod can be calculated. The range of hoop stresses tested in the matrix will be changed if the sister rod hoop stresses are higher than the maximum 80 MPa anticipated at 350°C.

1.1.3 Total Hydrogen Content

The *Overview* (Hanson et al. 2016) documented the marked difference in oxidation/corrosion behavior and the corresponding total hydrogen in the cladding as a function of burnup based on the cladding alloy. This dependence of total hydrogen on burnup is also true along the axial length of the fuel rod. The cladding temperature is a function of both the coolant temperature (that increases going up the axial height of the reactor core) and the local burnup. A typical burnup profile is shown in Figure 1. ORNL will obtain the actual burnup profile for each of the sister rods by gamma scanning (Montgomery et al. 2017).

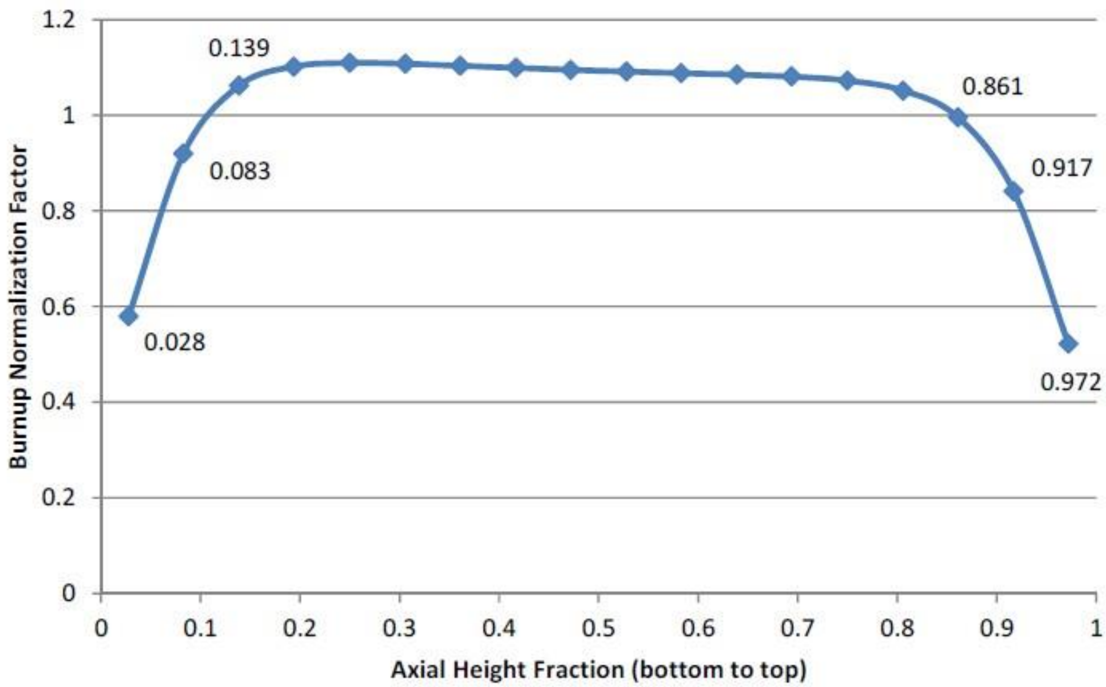

Figure 1. Representative PWR Axial Burnup Profile (Caciapouti and Van Volkinburg 1997).

From Figure 1, it can be seen that each rod should be divided into at least three different zones to account for potential variability in the oxide layer thickness and total hydrogen content

Zone 1: lower end (~20% of the rod length) with lower burnup, lower oxide thickness, lower total hydrogen

Zone 2: fuel-column mid-span region (~60% of the rod length) with high burnup, higher oxide thickness, higher total hydrogen

Zone 3: upper end (~20% of the rod length) with lower burnup but still higher oxide thickness and total hydrogen

Each zone includes portions of the cladding under the grid spacers. The cladding under the grid spacers is characterized by lower local burnup, oxide layer thickness, and total hydrogen content. Segments from under the grid spacers will be used for material properties tests to determine if possible grid-to-rod fretting (i.e., thinning of the cladding) results in earlier failure during burst or tensile testing.

1.2 Data Needs for Modeling Cladding Performance

It is not practical to test under all possible conditions, so modeling and analyses are used to predict fuel performance under various scenarios associated with extended storage and transportation, potentially followed by further storage and transportation. PNNL is performing most of the modeling and analyses for storage, including cask tip-over, drop, and seismic events, as well as for NCT (e.g., Klymyshyn et al. 2014, 2015).

1.2.1 Modeling Overview

Fuel rods are modeled using many numerical analysis methods for many different applications. The properties discussed in this test plan are needed for structural models, which analyze the fuel rod response to mechanical loads, like pressures, forces, vibrations, or other dynamic excitation. The two main branches of structural models cover static mechanical loads and dynamic mechanical loads.

An example of static mechanical loading is the pressure within SNF rods. An example of a static mechanical loading analysis application is determining whether or not rods will burst during a hypothetical fire scenario. Thermal and fire modeling is used to determine the peak temperature in the fuel rods during the thermal transient. The temperatures and associated internal pressure would then be applied to a structural model of the cladding. The structural model of the cladding could be resolved with as much detail as desired in terms of local cladding thickness, plenum space geometry, rod bowing, and any other fine detail that might affect the burst conditions. One point of interest regarding internal pressure loads is the degree to which pressure can communicate along the length of the rod. With perfect communication, the pressure is equal throughout the rod. If the pressure pathways are closed due to pellet swelling, there could be pressure cells of locally higher pressure. Modeling can be applied to determine the consequences of localized pressure cells, but testing like the sister rod campaign is needed to supply the relevant information. Currently, it is typical to rely on burst pressure databases to determine if rods will fail as a result of increased pressure and temperature. With sufficient test data, modeling can get to a much more realistic burst pressure assessment, based on the characteristics of individual fuel rods instead of relying on conservative database values.

An example of dynamic mechanical loading is the loading caused by a drop of a multipurpose welded canister (MPC) during handling, as when the MPC is being lowered into a vertical dry storage cask (DSC) system. The impact loads are transmitted through the components of the system to the fuel assemblies. The loading is primarily axial (in line with the long axis of the fuel rods) and has a very short duration (load pulse on the order of tens of milliseconds). In this type of loading condition, perfectly straight rods (as fabricated) do not behave the same as realistic irradiated rods, which often exhibit bowing. Models will often assume a sinusoidal bowing pattern between the spacer grids to try to achieve realistic behavior in the models, but the amount of bowing and the pattern of non-straightness in the fuel rods need to be assumed. This test campaign is expected to provide good information about bowing characteristics to help guide future modeling.

Another example of dynamic mechanical loading is the vibration response evaluation of SNF during normal conditions of transport. Whether the SNF is transported by truck, rail, barge or any other method, some amount of vibration loading is to be expected. The different transportation methods expose the fuel to different vibration environments, with excitation occurring at different magnitudes in each frequency band. Shaker testing has demonstrated that the fuel assembly responds more strongly in some frequency bands than others (Klymyshyn et al. 2014). Modeling suggests that the spacer grid spacing as well as the effective flexural rigidity (EI) of the fuel rods will determine to which frequency bands the fuel rods are most sensitive. The EI (where E is Young's modulus and I is the area moment of inertia for the cross section) is affected by the amount of burnup, the temperature, and the degree to which the fuel is bonded to the cladding. Cyclic integrated reversible-bending fatigue testing (CIRFT) has demonstrated that fuel rod effective EI is not a perfect composite (Wang et al. 2016). Realistic EI is approximately the EI of the cladding plus half the EI of the fuel pellets. For a given fuel assembly spacer grid geometry, the mode shapes and resonance frequencies will depend on the exact EI of the fuel rod. The sister rod testing at ORNL (Montgomery et al. 2017) will provide more information on effective EI.

1.2.2 Specific Data Needs

All the modeling examples provided in Section 1.2.1 need the information identified in the list below. When the data are not specifically available, the models have to make best estimate or conservative assumptions.

- Cladding outside diameter (OD)
- Cladding thickness
- Irradiated length of the fuel rod
- Total mass of the fuel rod (including cladding, fuel, end plugs, etc.)
- As-irradiated length of plenum spaces
- Temperature dependent:
    - Cladding modulus of elasticity and shear modulus or Poisson's ratio
    - Cladding yield strength
    - Cladding ultimate tensile strength
    - Cladding uniform plastic elongation (strain prior to the initiation of necking)
    - Bending rigidity (EI) of the cladding/fuel composite
- Strain rate dependent:
    - Cladding yield strength
    - Cladding ultimate tensile strength
    - Cladding uniform plastic elongation

1.2.3 How Data are Used in Models

Cladding OD and cladding thickness address the realistic configuration of the fuel rods. Models are often based on nominal, as-designed dimensions, but the expectation is that real fuel rods that come out of the reactor and go through cooling and drying processes will vary from the nominal configuration. Measurements of cladding OD and cladding thickness help establish the real cladding geometry, which affects the calculated stress and strain in all types of structural models. These measurement data are expected to reveal local thinning of the cladding, if present. Wear from fretting is expected to be noted in the NDE characterization. Oxide layer thickness also affects the actual amount of cladding material that is available to carry a structural load. The precision and accuracy of models can be increased by accounting for all the phenomena that can affect the cladding geometry.

The irradiated length of the rod and the irradiated length of the plenum spaces are similarly important to define the actual geometry of a fuel rod, so loads are properly transmitted and distributed through the fuel rod structure. The profilometry to be performed by ORNL (Montgomery et al. 2017) is expected to provide useful information about the amount of rod bowing that is present in the sister rods. Bowing can affect the dynamic response of fuel. Bowing can be very important in load cases with an axial dynamic load component, such as a handling drop into a vertical DSC. The amount of bowing can influence the location where the limiting stress and strain occurs along the fuel rod.

The total mass of the fuel rod helps round out the set of data that characterizes the fuel rod configuration for modeling. The various pieces of data, such as total length, plenum lengths, cladding diameter, and cladding thickness should all come together and tell a consistent story about the state of the fuel rod. Total mass is easy to measure, and it is necessary for dynamic models that require the fuel rods to have correct mass for energy balance and proper calculation of inertia loads. Models can use nominal values for mass and density, but greater precision and accuracy can be achieved when the models are based on data.

Temperature-dependent material properties are important to have because numerical modeling and analysis is often concerned with fuel rod loads that occur over a broad range of temperatures. In cases like fire scenarios, the models need material behavior information at temperatures that cover the full thermal transient (pre-fire, mid-fire, post-fire). Depending on the severity of the fire, temperatures can approach or exceed burst temperatures, so the material strength data can be very consequential. If precise and accurate material strength data are not available at the temperatures of interest, conservative material strengths have to be assumed, and this can force a modeling study into very conservative conclusions that have safety implications. Some of the value of the sister rod test campaign is in generating data that could help reduce conservatism in safety-basis calculations, which could benefit the nuclear industry by helping them eliminate unnecessary conservatism in design and operating practices.

The variation of temperature along a rod at any given time is also an issue that arises during modeling. Ideally, the temperature variation along the rod length would be known, and fuel rod material properties could be assigned by location to properly represent the fuel rod along its length. Modulus of elasticity, shear modulus, and poison's ratio affect the stiffness of the fuel rod, with cooler temperatures having relatively higher stiffness values. These properties affect model-predicted fuel rod response to loading.

The yield strength, ultimate strength, and plastic stress-strain behavior affect the response of cladding to mechanical loads in the plastic deformation range. Even though the ductility of the cladding material is reduced, it typically retains some capacity to plastically deform. Collecting plastic-range material data is needed to model behavior in the region of response between the elastic limit and the ductile failure limit. Stress-strain curves are not explicitly mentioned in the list in Section 1.1.2, but they are intended to be collected along with tensile and compressive material test data to support the use of elastic-plastic material models at various temperatures.

In interpreting the results of elastic-plastic structural models, cladding failure is typically defined at the uniform elongation limit, which is the point in a uniaxial tensile test where necking begins. Structural models that assume elastic material behavior can conservatively use the yield strength as a failure limit, or else base failure on the ultimate tensile strength, but the fact that elastic material models cannot account for strain hardening typically requires elastic models to adopt conservative failure criteria. The more test data that can be generated to support sophisticated material models, the better numerical models can simulate structural behavior under loading conditions that approach the material failure limit.

As models attempt to simulate cladding behavior under conditions that approach the cladding failure limit, the strain rate dependence of material strength becomes an issue in dynamic loading conditions. In handling drop dynamic load cases, or DSC tipovers caused by hypothetical earthquakes, the limiting mechanical loads can have a high magnitude, but can also be applied over a short duration. Materials tend to be stronger at higher strain rates, which means that using material strength data collected at low strain rates to judge failure of high strain-rate scenarios can be overly conservative. In dynamic loading scenarios, the peak strain rate can typically be on the order of 10 s^{-1}, with 100 s^{-1} being a reasonable upper bound . Importantly, limiting stress and strain results for cladding tend to occur at the highest strain rate, so higher strain rate strengths tend to be more appropriate than low strain rate values. As this test campaign is limited in material available for testing, the primary focus of the strain rate testing will be to determine if the real cladding material demonstrates any significant strain rate sensitivity. Most tests will be performed at low strain rates according to ASTM standards. A limited number of tests will be performed at a much higher strain rate (3 or more orders of magnitude higher) for comparison to the low strain rate tests. If strain rate sensitivity is significant, PNNL will consider using some of the remaining material in higher strain rate tests.

In LS-DYNA, the ideal material model is the power law plasticity model, which has proven to be less computationally expensive than other options (e.g., multilinear elastic-plastic material models). This model also has built-in strain-rate dependency, so it only accumulates plastic strain as appropriate for the current strain rate. This test campaign will collect the data needed to determine best-estimate model parameters for the power-law plasticity model. The strain rate dependency can be eliminated if the test data show that the material behavior is not sensitive to strain rate. Currently, the expectation is that strain rate could have a small but potentially significant effect on the material behavior, so it is not the highest priority parameter to test.

Compressive material testing is included in the test plan, but like the strain rate behavior, it is not a major priority. The purpose of doing compressive testing is to confirm that the material behaves as expected, and does not exhibit any unexpected weakness under compressive loading. Compressive loading is common in the loading conditions used fuel can potentially experience, so it is valuable to confirm the expectation that the compressive strength is equal to or greater than the tensile strength. One example of compressive loading is vibration loading during transportation, where one side of a bending fuel rod is in tension while the other is in compression. Another example is a handling drop scenario, where the fuel is initially in uniaxial compression before it starts to bend. The point of this test is confirm expectations, so only a small number of compression tests are planned, with more to be added if the results differ from expectations.

2. SISTER ROD CHARACTERISTICS

The *Overview* (Hanson et al. 2016) describes the characteristics of the donor assembly and individual sister rods and the methodology for choosing the rods. Table 2 identifies the characteristics of the 10 sister rods that will be tested at PNNL. Preliminary cutting diagrams for each rod are provided in Appendix A. These cutting diagrams will be modified to account for rod and pellet stack growth and location of grid spacers as identified in the NDE to be performed at ORNL prior to the rods being shipped to PNNL (Montgomery et al. 2017).

Table 2. Characteristics of PNNL Sister Rods.

Cladding Alloy Type	Donor Assembly Identifier	Sister Rod Lattice Location	Assembly Average Burnup (GWd/MTU)	Expected Rod Average Burnup (GWd/MTU)
M5®	5K7	C5	53.3	56.8
M5®	5K7	K9	53.3	54.0
M5®	5K7	P2	53.3	51.2
M5®	30A	P2	52.0	49.4
ZIRLO®	6U3	M3	52.7	57.4
ZIRLO®	6U3	O5	52.7	58.0
ZIRLO®	6U3	P16	52.7	49.6
ZIRLO®	6U3	L8	52.7	55.1
ZIRLO®	3F9	P2	52.3	49.0
Zr-4	F35	K13	57.9	na

The rods were chosen to maximize the variability in rod burnup to in turn maximize any potential variation in total hydrogen content, as discussed in Section 1.1.3. It is anticipated that ORNL will perform rod puncture, EOL RIP, gas analysis, and rod free volume measurements (Montgomery et al. 2017) on all 10 rods prior to them being shipped to PNNL as either full-length rods or by having each rod sectioned approximately in half and shipped in storage tubes. Upon receipt at PNNL, the 10 rods will each be sectioned into approximately ¼-lengths using a slow-speed saw (e.g., ISOMET) with a diamond-coated blade and water as a coolant. These segments (40 in total) will be stored in individually labeled and sealed tubes that have had inert gas pumped into them to facilitate storage until a section is to be used for testing.

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3. RADIAL HYDRIDE TESTS

The primary objective of PNNL testing of sister rods is to extend the applicability of the High Burnup Spent Fuel Data Project by determining the temperature and hoop stress combinations that result in sufficient radial hydride formation to affect material properties and cladding performance. This will be done for the M5® and ZIRLO® rods using the radial hydride treatment (RHT), or simulated drying procedure, developed by Billone (Billone et al. 2013a, 2013b) at Argonne National Laboratory (ANL). Samples of the segments that have undergone RHT will then be sent to ANL for ring compression testing (RCT) that is used to determine the remaining ductility of the cladding under a pinch load and a series of RCT is used to determine the ductile-to-brittle transition temperature[a] (DBTT).

As shown in Section 1.1.1, the PCT of sections of rods that were hot enough to support sufficient radial hydride formation, assuming a high enough hoop stress, will be above 100°C for at least 100 years. Similary, Raynaud and Einziger (2015) estimated that it takes 300 years for cladding temperatures that were at 400°C to decrease to 100°C. The MCT, as shown previously in Table 1, is expected to be approximately 50°C at 300 years. Even though the areas of MCT are not expected to have significant radial hydride formation, for the purpose of this study, we will set 50°C as the threshold for DBTT. That is, if the DBTT of a sample is above 50°C, we will consider the t0' condition as significantly different from the t0 condition. This threshold is very conservative for all times less than 300 years.

RCT will be performed on defueled cladding segments. The justifications for using defueled segments are:

- It allows direct comparison with data generated to date for both NRC and DOE programs (e.g., Billone et al. 2013a, 2016)
- NRC staff recently presented that "Use of cladding-only mechanical properties in approved design-bases analyses is adequate and conservative" (Torres 2016)
- While it can be expected that the presence of the fuel will limit displacements under both pinch and bend modes, the conditions under which a sufficient fuel/clad bond form or breakdown are not well established and thus the use of cladding-only properties are warranted until additional information, such as will be obtained at ORNL (Montgomery et al. 2017), are known.

It is important to stress that even though NRC staff (Torres 2016) have stated that for a 30-ft drop, pinch-type loads are insufficient to compromise cladding integrity and that it is no longer necessary to demonstrate that cladding temperatures are above the DBTT, such thoughts have not yet been codified in regulations or guidance. Similarly, as stated in the original DOE gap analysis (Hanson et al. 2012), the DOE program must be concerned about cumulative effects and very long terms, including for disposal, and the data obtained testing sister rods supports those efforts.

3.1 RHT Test Matrix

Because of the large range of temperature and hoop stresses that cladding may experience in dry storage, it is necessary to determine the temperature/hoop stress thresholds for each of the cladding types. As demonstrated in the Korean program on unirradiated, pre-hydrided cladding with a uniform hydride

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[a] Clarification is needed to avoid confusing the traditional meaning of the term DBTT with the way it is being used to describe the effects of radial hydrides under pinch loading, as shown by RCT. This is a direction-dependent structural behavior-not a material property-whereas the traditional usage of DBTT describes a material property regardless of how it is used in the structure.

distribution, the hoop stress at which hydrides reorient is lower at higher temperatures (Kim et al. 2015). Since radial hydride formation is heavily influenced by the original total hydrogen content as well as the hydride distribution and orientation, the three zones described in Section 1.1.3 as well as the range in burnups between rods will be used to maximize variability. With the two cladding types, M5® and ZIRLO®, each having three zones, the result is six cladding combinations to test at the various temperature and hoop stress combinations.

The full range of temperatures discussed in Section 1.1.1 is from a low of 138°C to the regulatory guidance limit (NRC 2003) of 400°C. However, the cladding temperature must be above about 250°C for more than 50 ppm of hydrides to dissolve upon heating. The range of hoop stress is from 60 MPa to as high as 120 MPa for IFBA rods (Hanson et al. 2016), though for standard rods the range is more likely 60 MPa to 95 MPa. For each of the six cladding combinations, this results in a matrix as represented in Figure 2. Final temperature and hoop stress ranges will be verified based on the thermocouple readings from the Research Project Cask (expected by August 2017) and the EOL RIP measured by ORNL prior to rod shipment.

Temperature (°C)	**Hoop Stress (MPa)**						
	60	70	80	90	100	110	120
250							
275							
300							
325							
350							
375							
400							

Green represents minimal hydride reorientation; Yellow represents obvious hydride reorientation but DBTT<50°C; Red represents significant hydride reorientation and DBTT≥50°C. Representative only.

Figure 2. Representative RHT Test Matrix.

Since the number of samples available for testing is limited, the testing will focus mainly on the combinations within the dashed lines. Even then, the real interest is when the t0' properties are different from the t0 properties, so the main attention is on the combinations at the transition between the yellow and red boxes.

A sample will have the RHT performed at a specified temperature (e.g., 325°C) and hoop stress (e.g., 70 MPa). After RHT, a metallographic sample will be prepared, and the radial hydrides characterized using the procedure for determination of radial hydride orientation fraction found in standard B811 (ASTM 2013) and the radial hydride continuity factor (Billone et al. 2013a) will be determined. Some of the specimens will then be sent to ANL for RCT. A second sample will have the RHT performed at the same temperature, but the next higher hoop stress and the post-RHT analyses repeated. By performing these tests, the threshold for significant hydride reorientation as a function of alloy type, total hydrogen content, temperature, and hoop stress will be determined. The process will continue until the DBTT as determined by RCT is above 50°C (i.e, the box is red). The next higher temperature will then be tested, again until the DBTT is above 50°C. It will be assumed that for any given temperature, once a "red box" is identified, the boxes will also be red for all higher hoop stresses. Similarly, for a given hoop stress, once a "red box" is identified, the boxes will also be red for all higher temperatures. This database will provide DOE and the industry with valuable information regarding conditions under which hydride reorientation becomes detrimental to cladding performance.

Figure A1 shows that there are six samples for RHT/RCT testing in Zone 1 for each of rods 5K7/C5 and 5K7/P2 with estimated rod-average burnups of ~57 GWd/MTU and ~51 GWd/MTU, respectively. Each rod will also have 17 samples in Zone 2 and eight samples in Zone 3. If the difference between the two rods or between zones is minimal, the number of samples in Zone 2 for the second rod will be reduced so the material can be used for material properties testing. Figure A2 shows similar results for the ZIRLO® rods 6U3/M3 and 6U3/P16 with estimated rod-average burnups of ~57 GWd/MTU and ~50 GWd/MTU, respectively, other than there only being five samples for each rod in Zone 1.

3.2 RHT Test Method

This section will outline the procedures and processes for performing the simulated drying or RHT and the RCT as developed by Billone (Billone et al. 2013a, 2013b).

3.2.1 Segment Cutting

A written test instruction will identify the storage tube to be retrieved in the PNNL High Level Radiochemistry Facility (HLRF) hot cells in the Radiochemical Processing Laboratory (RPL). The fuel will be removed from the inerted storage tube and the 3-inch (76 mm) segments cut using a slow speed saw (e.g., ISOMET) with a diamond coated blade. Water will be used as a coolant and to reduce the risk of sparking from zirconium fines. The cuts will be made according to the final cutting diagrams, which will modify the preliminary cutting diagrams found in Appendix A and accounting for rod and pellet stack growth, location of grid spacers, anomalies detected in the gamma scan performed by ORNL, and material loss from cutting.

3.2.2 Defueling

The first step of defueling will occur in either the HLRF or the sample will be transferred to the Shielded Analytic Laboratory (SAL) hot cells in the RPL. A small-bore core drill with a diamond-tipped bit or a typical drill also with a diamond-tipped bit will be used to cut through the fuel. At all times, extreme care must be taken to not stress the cladding from the interior with too large of a drill bit or from the exterior when clamping the cladding in place. Clamps or grips should always be on the ends of the sample and no more than 15 mm from the end of the sample. An alternative method for defueling being explored is using an ultrasonic bath of water with the frequency set to pass through the cladding and break apart the fuel. Once enough of the solid fuel has been removed, the sample will be transferred to the SAL hot cells. The samples will then be connected using hose clamps to tubing to allow hot nitric acid to be pumped through the cladding inner diameter. This will continue using various concentrations of nitric acid until the fuel has all been dissolved. The flowthrough system is used to prevent excess fission products and actinides from being sorbed in the CRUD or oxide layers on the cladding OD in an attempt to minimize sample dose for future operations. An alternative is to put the sample in a beaker of hot nitric acid to dissolve the fuel. A second alternative is to use an ammonium carbonate/hydrogen peroxide mixture to dissolve the fuel per a PNNL-patented process.

3.2.3 RHT Sample Preparation

The OD of the segment will be measured at a minimum of two orientations (90° apart) and at a minimum of three axial locations. These values are averaged to give the OD used to calculate the hoop stress. The oxide layer thickness will be estimated based on the measurements performed at ORNL and from adjoining samples in order to calculate the cladding wall thickness and thus the ID which is necessary for calculating hoop stress.

If the samples are sufficiently round and uniform, it may be possible to use Swagelok fittings for the sample pressurization, especially since the hoop stress (and thus internal pressure) and temperatures are lower than have been previously performed by Billone (e.g., Billone and Burtseva 2016). If not, then a welding technique will be used. First, the oxide layer and any remaining fuel will be machined from approximately 15 mm on each end of the segment. A zirconia pellet may be inserted into the rodlet to reduce internal stored energy. Next bottom and top end fixtures, most likely made from Zircadyne-702, will be welded to the segment. The rodlet will then be pressurized using an inert gas (argon, helium, nitrogen) to the room temperature pressure that will correspond to the at-temperature pressure for the desired hoop stress. The fixtures will be sealed, most likely using laser welding. Figure 3, taken from Billone et al. 2013, shows an example of a non-irradiated cladding segment before (upper photo) and after (lower photo) fabrication of the pressurized rodlet.

Figure 3. Example of Rodlet Fabrication (Billone et al. 2013b).

3.2.4 RHT Thermal Treatment

The sealed, pressurized rodlets will be placed in a furnace. The furnace will be heated to the desired temperature, representing the PCT during drying. Once the temperature has stabilized, the rodlet will be held at that temperature for at least one hour, but as specified in the test instruction. The rodlet will then be cooled slowly at no more than 5°C/hr to allow the hydrides to precipitate, nucleate, and grow. Once the temperature reaches about 100°C, representing less than 20 ppm hydrogen still in solution, cooling can be accelerated until the rodlet reaches room temperature.

3.2.5 Post-RHT Examination

After cooling, the rodlet will be sectioned, again using a slow speed saw with a diamond-coated blade and water as a coolant, according to a sectioning diagram similar to Figure 4, taken from Billone and Burtseva (2016). Both ends will be discarded to avoid end effects created by the Swagelok or welding processes. At least three rings of 2 mm thickness will be cut and used for total hydrogen analysis using the inert gas fusion technique (e.g., LECO hydrogen analyzer). Each ring will be sectioned into quarters and analyzed individually. This allows the circumferential variation in total hydrogen content to be determined. At least one ring of 3 mm thickness will be mounted, polished, and etched as necessary for metallographic analysis using both optical and scanning electron microscopy. The metallography facilitates the calculation of both the radial hydride orientation fraction following standard B811 (ASTM 2013) and the radial hydride continuity factor (Billone et al. 2013a). The actual oxide layer thickness for the sample to accurately calculate the actual hoop stress will also be determined from the metallograpy.

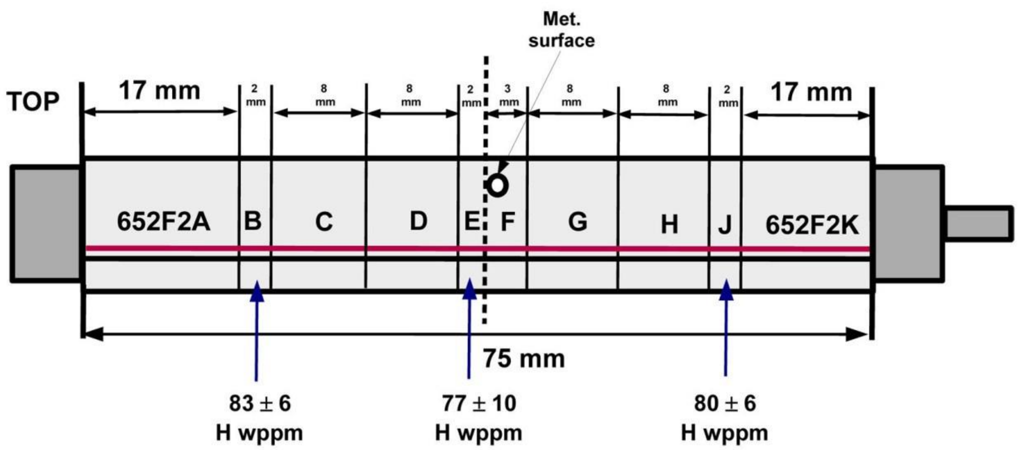

Figure 4. Example of Rodlet Sectioning for Post-RHT Examination (Billone and Burtseva 2016).

3.2.6 RCT

At least three, if not four, sections of approximately 8 mm long will be cut from the post-RHT rodlet and sent to ANL. RCT at three or four temperatures from room temperature to about 150°C will be conducted using a 5 mm/s displacement rate to a maximum displacement of 1.7 mm. The load vs. displacement curves produced are used to determine the DBTT. Staff at ANL and PNNL will communicate often and discuss the results to determine if modifications to the test matrix are needed and what samples and RHT conditions should be run next. Figure 5 shows the RCT sample in the load frame at ANL

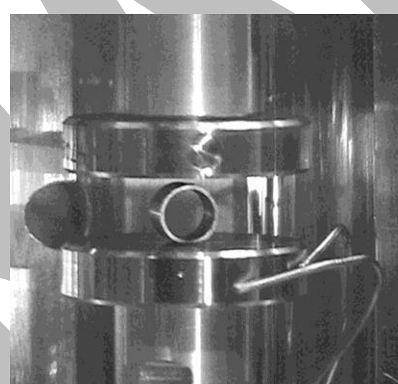

Figure 5. RCT Sample in Load Frame at ANL (photo courtesy of Mike Billone at ANL).

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4. MATERIAL PROPERTY TESTS

The second objective of the PNNL sister rod testing is to obtain the t0' material properties for use in modeling of cladding performance. Mechanical properties of defueled cladding will be determined using standards and methodologies approved by ASTM International (ASTM). These methods include tube axial tensile tests, tube burst tests, and tube compression tests.

Cladding will have natural variation and defects associated with its fabrication and its irradiation history. One of the primary factors of interest is the hydride concentration and distribution prior to RHT. Billone et al. (2013a, 2013b) have shown that the total hydrogen concentration can vary dramatically both from one quarter-ring sample to another at the same elevation on a rod and even more so by axial location even for adjacent samples. This is also true of the oxide layer thickness, which is proportional to the amount of cladding thinning that occurs. However, the circumferential variation in hydride content is much greater than the circumferential variation in oxide layer thickness. Other defects, such as can occur from grid-to-rod fretting at the spacer grids, will be located throughout a rod. PNNL staff considers it of high importance to test relatively large segments of cladding so that failure will naturally occur at the weakest or most damaged location. Testing multiple, large segments will give the greatest reproducibility while accounting for the significant variations within the material. Similarly, the authors of the models that use the existing material properties database (Geelhood et al. 2008, 2013) have confirmed that the best data comes from biaxial burst tests and axial tension tests on full tubes (no machining of the tubes to make mini dogbones)[b].

Acceptance of manufactured cladding by the fuel vendor typically requires successful demonstration of full tube cross section axial tensile tests (Sandvik 1989). These tests are performed using a universal test (load) frame set to strain the sample at a constant rate. The load-displacement data produced are converted to stress-strain data, an example of which is shown in Figure 6. The yield strength, ultimate tensile strength, work hardening rate, and uniform plastic elongation can be determined directly from such curves and/or from the digital data used to generate these curves and then used in constitutive relations in finite element modeling. Yield strength and ultimate strength are determined in the same manner as is typical for ASTM tensile testing (0.2% offset and engineering stress at peak load), while the work hardening rate is determined by fitting a typical flow curve[c] (e.g. $\sigma = K\varepsilon^n$). The uniform plastic strain is determined as the value of the plastic strain at the point of necking.

This test will provide the data necessary to implement a power law plasticity model for the cladding material in LS-DYNA, which is a computationally effective material model. This model is useful in all static and dynamic structural models that explore fuel cladding behavior under applied loads. Strain-rate dependent behavior can be implemented in this model, whether the strain rate sensitivity is high or low. If the strain rate dependency is negligible, the strain rate exponent can be set to zero to eliminate the strain rate dependence. While the power law plasticity model is the preferred choice, the data might show that stress-strain behavior is better represented by some other elastic-plastic material model. Either way, these test data will help improve the accuracy of the structural models in the plastic range, by providing a database of test data that numerical models can be validated against. The value of this development is to be able to credibly model cladding material behavior in the range that is near the failure limit, which will allow modeling to eliminate conservative assumptions.

[b] Personal communication from Ken Geelhood to Nick Klymyshyn, January 2017.

[c] σ and ε are the true stress and strain respectively, while K and n are the strength coefficient and work hardening rate respectively

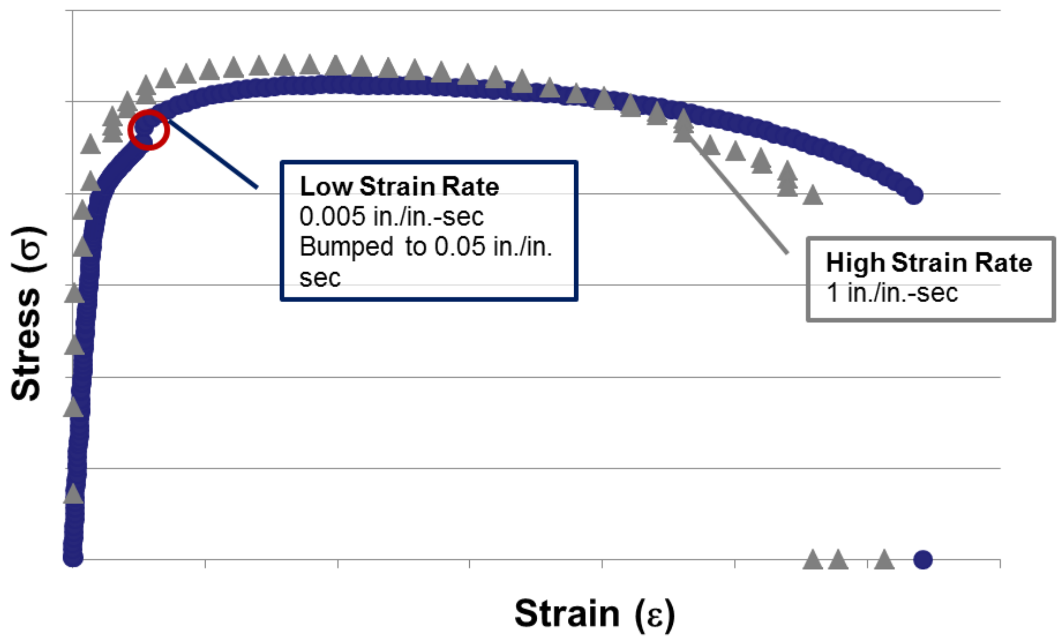

Figure 6. Example of Axial Tensile Stress-Strain Curve. (Shimskey et al. 2015)

Zirconium-based cladding is often anisotropic, though texture and irradiation may alter this. As such, and because of the concern of cladding bursting under a loss of coolant accident or a reactivity-initiated accident during irradiation, the tube burst test is also a standard means to examine biaxial stress and to determine the ultimate hoop strength and percent total circumferential elongation, as described in ASTM standard B811 (ASTM 2013). In addition, it has become a test used by many nations and companies to determine mechanical properties and cladding performance, including the effects of radial hydrides (e.g., Bouffioux et al. 2013, Nagase and Fuketa 2005, NRC 2001). An example of the effect of hydrides on unirradiated, pre-hydrided cladding burst performance is shown in Figure 7.

Figure 7. Unirradiated, Pre-Hydrided Cladding after Burst Testing. (Shimskey et al. 2015)

The purpose of doing compressive testing is to confirm that the material behaves as expected, and does not exhibit any unexpected weakness or change in behavior under compressive loading. Compressive loading is common in many of the mechanical loading scenarios explored through numerical modeling, so it is valuable to confirm the expectation that the compressive strength is equal to or greater than the tensile strength. One example of compressive loading is during cyclical vibration loading during used fuel transportation, where one side of a bending fuel rod is in tension while other is in compression. Another example is a handling drop scenario, where the fuel initially experiences a uniaxial compression pulse before it starts to bend. The point of this test is confirm expectations, so only a small number of compression tests are planned, with more to be added if the results differ from expectations.

4.1 Material Properties Test Matrix

Ideally, multiple rodlets would be prepared using one specific RHT (i.e., PCT and hoop stress combination) and then multiple (at least six each) tube tensile, tube burst, and tube compression tests would be performed at room temperature. The series would then be repeated with the material properties tests performed at multiple, elevated temperatures to determine the temperature-dependency of the material properties. The series would also be repeated by increasing the strain rate during the tests to determine the strain rate-dependency. The entire matrix would then be repeated at a different RHT condition. However, not only is there not enough sister rod material to perform such a matrix, but the cost would be prohibitive.

The final material properties test matrix will depend heavily on the results of the RHT testing as well as from the initial material properties tests. Some material properties tests must be performed on samples after RHT at the upper range of temperature and hoop stress expected for standard rods under current industry loading practices (e.g., 325°C and 80 MPa) even if the DBTT is below 50°C (i.e., yellow box in Figure 2). This is to determine whether existing t0 material properties can be used to model fuel that has been dried and is thus in the t0’ condition. If t0’ properties differ significantly from t0 properties, then the focus needs to be on determining t0’ material properties under these RHT conditions. Next, material properties tests should be performed on samples after RHT near the maximum, realistic temperature and hoop stresses (e.g., 375°C and 95 MPa) that can occur if loading practices are more aggressive.

This test plan presents the proposed matrix for only the first series of tests, which will use all of the material from one rod. The final matrix will be developed after those results are analyzed and compared against existing databases to guide the testing to most efficiently use the limited material and to collect the data that will have the highest impact on accurately modeling HBU SNF under storage and transportation conditions. Testing will start with ZIRLO® because there will be three rods available as opposed to only two for M5®. Appendix A-2 shows the preliminary cutting diagram for rod 6U3/O5 with a rod-average burnup of ~58GWd/MTU. This rod will supply 22 6-in segments, one of which is the upper plenum area within Zone 3 that contained no fuel, and eight of which were located under grid spacers and may have fretting or other wear that could affect their performance under testing. In Zone 2, there are 11 of the segments, three of which were located under a grid spacer. In Zone 4, there are seven total 6-in segments counting the one for the upper plenum and two under grid spacers. Table 3 outlines the conditions and testing for the first series.

The methodology for developing the remaining test matrix is as follows:

1. Compare data from samples with no RHT (i.e., t0) to data from samples with RHT from the upper range of expected temperature and hoop stress (e.g., 325°C, 80 MPa). If the t0’ data is not significantly different from the t0 data, then the final test matrix will focus on higher temperatures and hoop stresses for the RHT. If the t0’ data are statistically different, then the final test matrix will focus on material properties using this RHT condition, but over a broader range of test temperatures, including more burst testing.

2. Compare data from Zone 2 samples with data from Zone 1 and Zone 3 samples tested under identical RHT and test conditions. If the material properties are not significantly different, it will be assumed that the difference in burnup and total hydrogen within the range available does not matter. Testing on the other two rods will then focus on other RHT conditions, tensile and compression tests performed at higher temperatures, more burst testing, and investigating the potential strain rate dependence. If the material properties are different, then the matrix for rod 3F9/P2 with a burnup of ~49 GWd/MTU will be similar to the matrix for rod 6U3/O5 to help quantify the material property dependence on burnup and total hydrogen content.

3. Compare the data for the compression tests on the seven specimens identified in Appendix A-2 with data from tensile tests for samples with identical RHT. If the material properties under compression are significantly different from the tensile properties, the future matrix will incorporate more compression tests at the expense of testing at higher RHT conditions.

4. Once the relative dependence on burnup, RHT, and test temperature is known, the samples from under the grid spacers will be tested to determine if fretting or wear had any effect on the cladding performance.

5. The final data analysis on the ZIRLO® rods will be used to develop the test matrix on the two remaining M5® rods and the one Zr-4 rod.

Table 3. Proposed Test Matrix for ZIRLO® Rod 6U3/O5.

Zone	Segment	RHT Condition (temperature, hoop stress)	Test	Test Temperature (°C)
1	1	None	Tensile	RT
	2	325°C, 80 MPa	Tensile	RT
2	1	None	Tensile	RT
	2	None	Tensile	RT
	3	325°C, 80 MPa	Tensile	RT
	4	325°C, 80 MPa	Tensile	RT
	5	325°C, 80 MPa	Burst	RT
	6	325°C, 80 MPa	Burst	RT
	7	325°C, 80 MPa	Tensile	200
	8	325°C, 80 MPa	Tensile	200
3	1	None	Tensile	RT
	2	None	Tensile	RT
	3	325°C, 80 MPa	Tensile	RT
	4	325°C, 80 MPa	Tensile	RT

4.2 Material Properties Test Methods

This section outlines the different test methods to be used to determine material properties. All samples will follow the same methods for segment cutting, defueling, sample preparation, and RHT thermal treatment as outlined in Sections 3.2.1 through 3.2.4, with the exception that the few samples tested at t0 conditions will not have the RHT thermal treatment. The other differences are that the segment lengths will be according to the final cutting diagram and additional OD measurements will be performed according to ASTM procedures.

4.2.1 Axial Tube Tensile Tests

This test is done in accordance with ASTM International Standard E8 (ASTM 2015) and B811 (ASTM 2013). All of the sister rods come from 17×17 PWR assemblies with the cladding OD of 0.374 in (0.950 cm). For tubing of this small diameter, it is recommended to use full tube cross sections with a gauge length of at least 4×OD. PNNL staff plan to use 6-in length defueled segments with snug-fitting metal plugs of approximately 1 in on each end with a pin through the plug and sample to allow proper gripping of the sample (see Figure 8). The gauge length will thus be approximately 4 in compared to the minimum 1.5 in required by the standard. An extensometer is used to measure elongation under loading and this is used in conjunction with digital image correlation (DIC), or speckle-pattern analysis. For DIC, the sample is painted with a speckle-pattern (see Figures 7 and 8) and cameras are used to record the movement of the speckles with time. The addition of DIC capabilities to a traditional ASTM tensile test provides three dimensional strain data, whereas an extensometer only provides axial strain data. The additional circumferential and radial strain data can be utilized to evaluate the crystallographic texture of the tubes, similar to a contractile strain ratio test (CSR) which is commonly used as a certification test of fuel cladding (Sandvik 1989). The CSR value is calculated as the ratio of circumferential to radial strain observed on a specimen that has been loaded in tension to an axial strain value of about 4% (Sandvik 1989). CSR provides a qualitative measure of texture as tubes with a high CSR value will have more basal poles oriented in the radial direction compared to tubes with a low CSR value (Sandvik 1989).

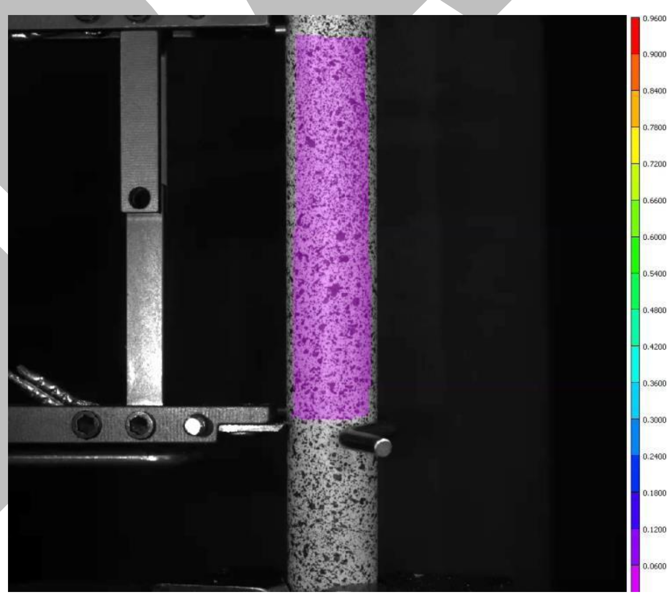

Figure 8. Example of Zircaloy Cladding Under Axial Tensile Load. (Shimskey et al. 2015)

The universal test frame to be used for this testing is located in a modular hot cell in the RPL at PNNL as shown in Figure 9. These tests are performed by setting the universal test frame to strain the sample at a constant rate. The ASTM standard (ASTM 2013) recommends a strain rate of between 0.003 to 0.007 mm/mm/min. For tests to determine a strain rate dependence, a strain rate of 3 to 4 orders of magnitude higher will be used. After testing is complete, samples will be cut from different locations both far from the break and at the break to determine total hydrogen content using an inert gas fusion technique. Samples will also be mounted, polished, and etched as necessary for metallographic examination to allow calculation of both the radial hydride orientation fraction following standard B811 (ASTM 2013) and the radial hydride continuity factor (Billone et al. 2013a) as well as to determine the actual oxide layer thickness.

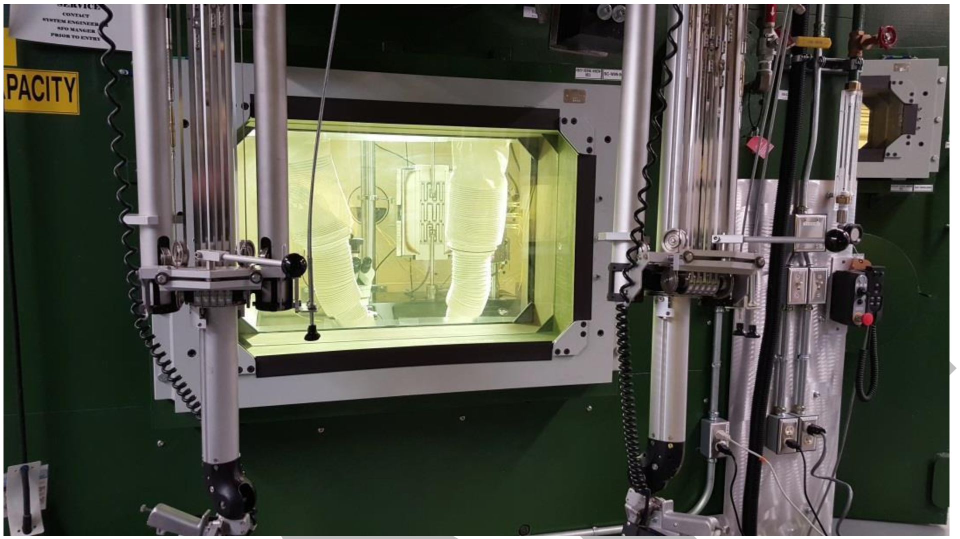

Figure 9. Universal Test Frame in Hot Cell.

4.2.2 Tube Burst Tests

The procedure for performing tube burst tests for acceptance of zircaloy cladding is found in ASTM B811 (ASTM 2013). The PNNL burst pressurization system is shown in Figure 10. A stepper motor, at right, drives an intensifier, which provides a controlled pressure ramp to the specimen. The motor is directed to run at a constant rate, which provides a nearly-linear pressure pulse without a pressure surge to the specimen. A DIC system employing eight high-resolution cameras (see Figure 11) is used to determine strain in three dimensions at frequent intervals prior to burst. Again, the plan is to perform multiple runs under identical conditions using a 6-in sample of defueled cladding to maximize variability within a single sample.

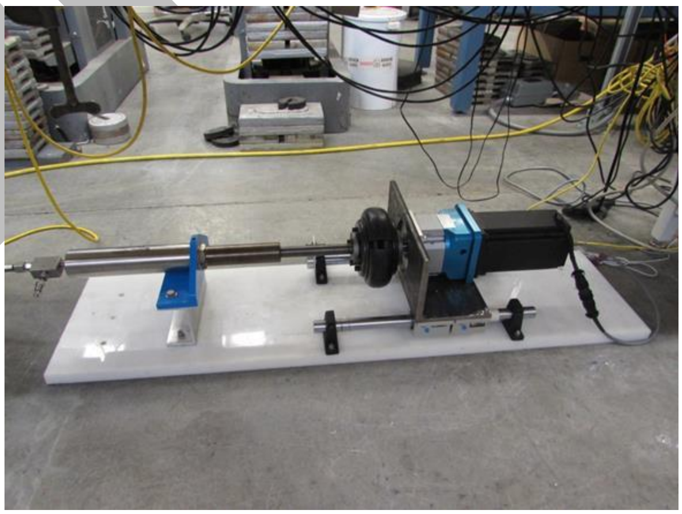

Figure 10. PNNL Burst Pressurization System. (Shimskey et al. 2015)

Figure 11. Burst Testing System with Digital Camera-Pairs. (Shimskey et al. 2015)

The data acquisition system records pressure, and the pressure and calculated strain provide details of the three dimensional strain in the specimen throughout the tests. The DIC system captures eight images of the specimen at predetermined intervals, and then determines the strain over the specimen surface by calculating the movement of discrete points on the specimen relative to a reference point. The fixtures on the top and bottom of the tubular specimen shown in Figure 11 are used to hold the specimen in place while applying water pressure from the pressurization system. Over the temperature range of interest for sister rod testing, pressurization using liquid has been shown to be satisfactory (NRC 2001), however, at elevated temperatures, an oil with a high boiling point, ignition temperature, and flash point would need to be used. Another option at elevated temperature is to use a gas, but to fill the tube with a metal rod to reduce the total volume and stored energy of the system. PNNL has experience using this system at room temperature, but additional modifications and testing would be needed to perform higher temperature burst tests.

Results from testing of pre-hydrided cladding (Shimskey et al. 2015) have shown similar results as Nagase and Fuketa (2005) that hydride concentration and distribution (rim vs. uniform) may not affect the burst pressure, but it does affect the type of failure (see Figure 2-7) and the strain at failure. An example of DIC strain analysis on unirradiated Zircaloy during a burst test is shown in Figure 12.

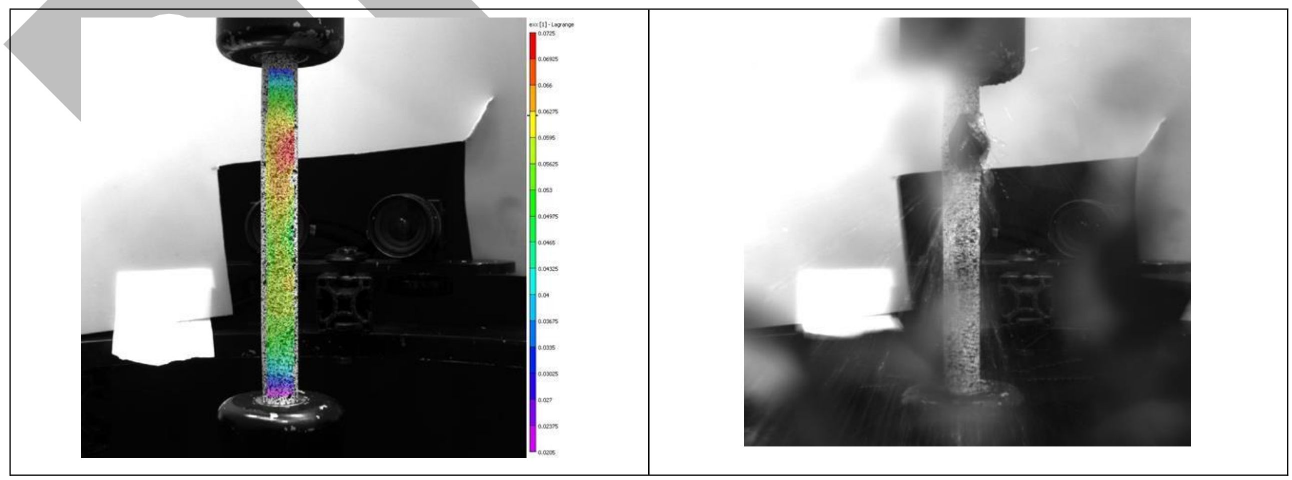

Figure 12. DIC Strain Analysis of Zirconium Cladding During Burst Testing Before Failure (left image) and After Failure (right image). (Shimskey et al. 2015)

After testing is complete, samples will be cut from different locations both far from the break and at the break to determine total hydrogen content using an inert gas fusion technique. Samples will also be mounted, polished, and etched as necessary for metallographic examination to allow calculation of both the radial hydride orientation fraction following standard B811 (ASTM 2013) and the radial hydride continuity factor (Billone et al. 2013a) as well as to determine the actual oxide layer thickness.

4.2.3 Tube Compression Tests

This testing follows ASTM International standard E9 (ASTM 2009) with modifications made according to standard E-111 (ASTM 2010) when the modulus of elasticity is to be determined. Given the cladding OD of 0.374 in, a specimen with length of approximately 1.5 in has a L/D ratio of 4 and is thus classified as a medium-length specimen which are used for determining the general compressive strength properties of metallic materials. In order to achieve the necessary flatness of both ends of the specimen, an approximately 3-in segment will be cut and machined on both ends. The data obtained from these tests may include the yield strength, the yield point, Young's modulus, the stress-strain curve, and the compressive strength. An example of an unirradiated cladding sample undergoing tube compression testing and using DIC is shown in Figure 13.

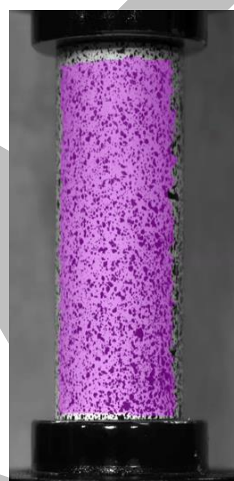

Figure 13. Example of Tube Compression Testing with DIC. (Shimskey et al. 2015)

4.3 Weibull Analyses

While most material properties are considered to be intrinsic and thus deterministic, the reality is that most manufactured materials are examined probabilistically to account for flaws created during fabrication, as well as differences in geometric parameters fabricated within specific tolerances (e.g., outer and inner diameters). In the case of irradiated cladding, the flaws could also include the variable oxide layer thicknesses, hydride content, distribution, and orientation, or defects such as from grid-to-rod fretting. While the Gaussian distribution is commonly used, the ceramic industry prefers to use the Weibull distribution for examining strength properties, because it does a better job of describing brittle materials. The Weibull distribution was selected because zirconium hydride is considered a ceramic material that is very brittle. Zirconium hydrides in Zircaloy behave like flaws in the matrix causing reduction in ductility where the flaws are present. For this reason, this type of analysis was selected to understand how variability in mechanical properties changes when the hydrides are present, and how that differs with unirradiated and irradiated material.

Cumulative Weibull distributions will be fitted to the mechanical properties measured from the destructive testing done for each cladding type. The results will be plotted against each other on a Weibull probability plot as in the example in Figure 14. In this figure, the distribution is plotted in a manner that it appears linear. The slope of this line is called the Weibull modulus. When the slope of the linearized distribution increases, the material is more reliable (i.e., less variability). As the slope decreases and becomes horizontal, the performance of the material (e.g., ultimate tensile strength or uniform elongation) is more variable, likely a result of flaws in the material. For most metals, the Weibull modulus is greater than 20, while ceramic materials are usually 10 or less.

The advantage of using the Weibull analyses is that it allows the probability of failure to be determined in "a chain with the weakest link" where the weakest link could be a manufacturing defect, a high hydride radial continuity factor, or thinned cladding from grid-to-rod fretting. It is typically advisable to have a large (>30) number of samples to plot in order to determine the Weibull modulus. Such a large number of samples is not practical given the cost of testing highly radioactive spent fuel cladding and the limited material available. For the analyses on unirradiated cladding, PNNL staff has shown that most properties will produce a linear line and that six to nine tests are sufficient (Shimskey et al. 2015). The use of the larger specimens for testing helps justify a smaller number of repeat tests. However, when the data are plotted, if it is highly non-linear, then additional tests may be performed for that parameter. As discussed in Section 4.1, there will not be enough material for six duplicate tests. More likely, only two or three duplicates will be run for each cladding type and under each condition. Still, plotting the results together on a Weibull plot will be useful in showing if any grouping, such as the samples that were under grid spacers, has a higher probability of failure.

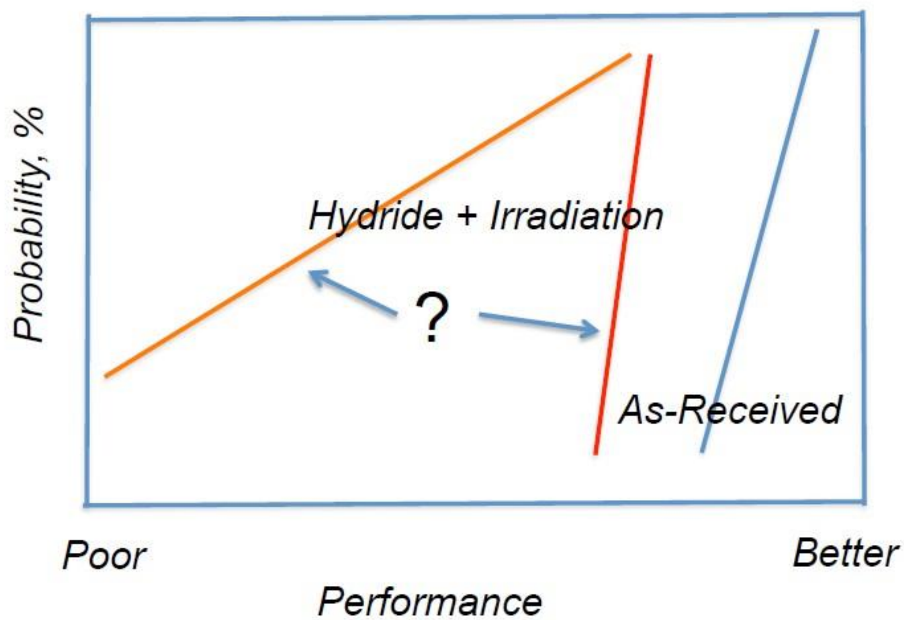

Figure 14. Example Weibull Plot.

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Appendix A

Preliminary Rod Sectioning Diagrams

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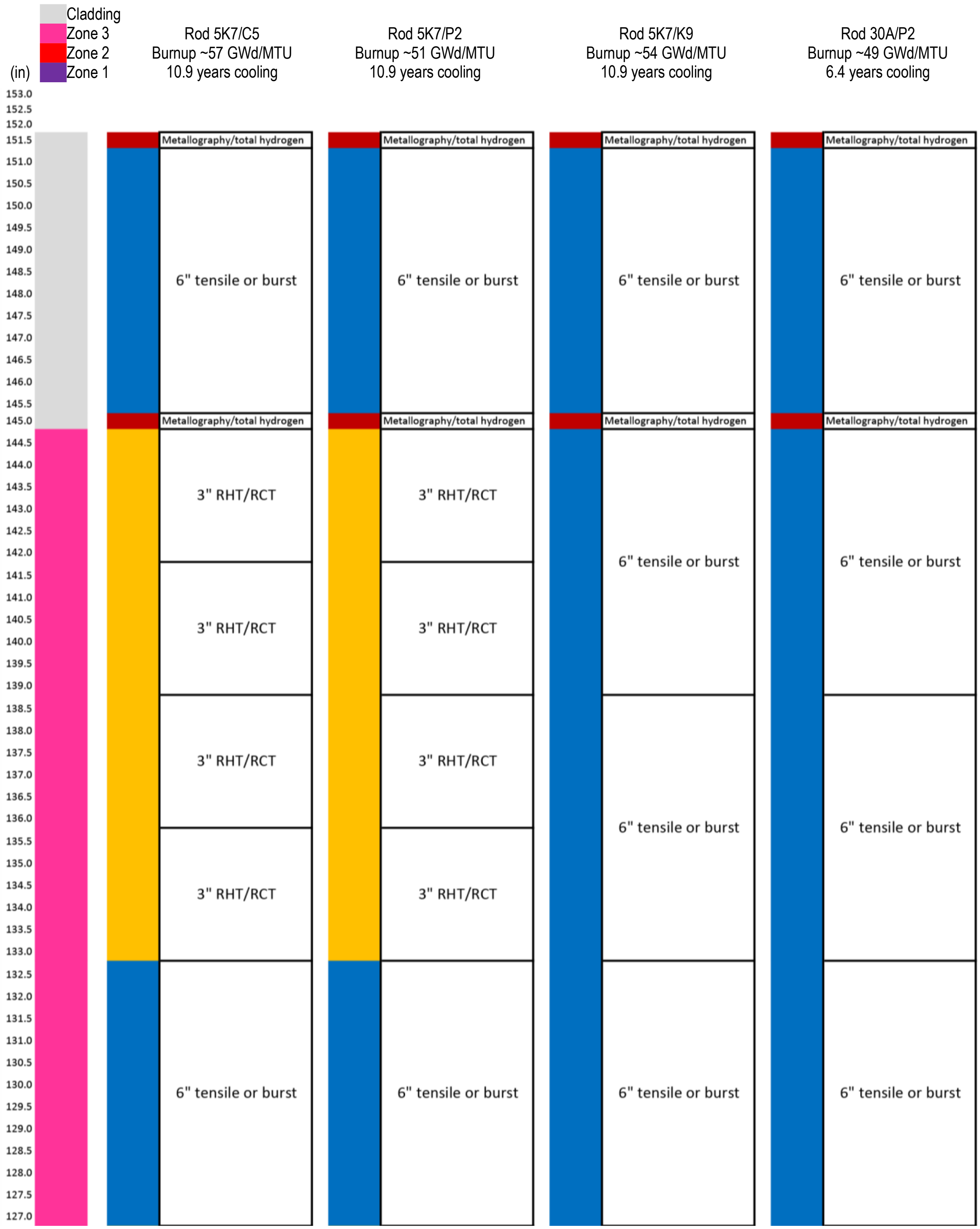
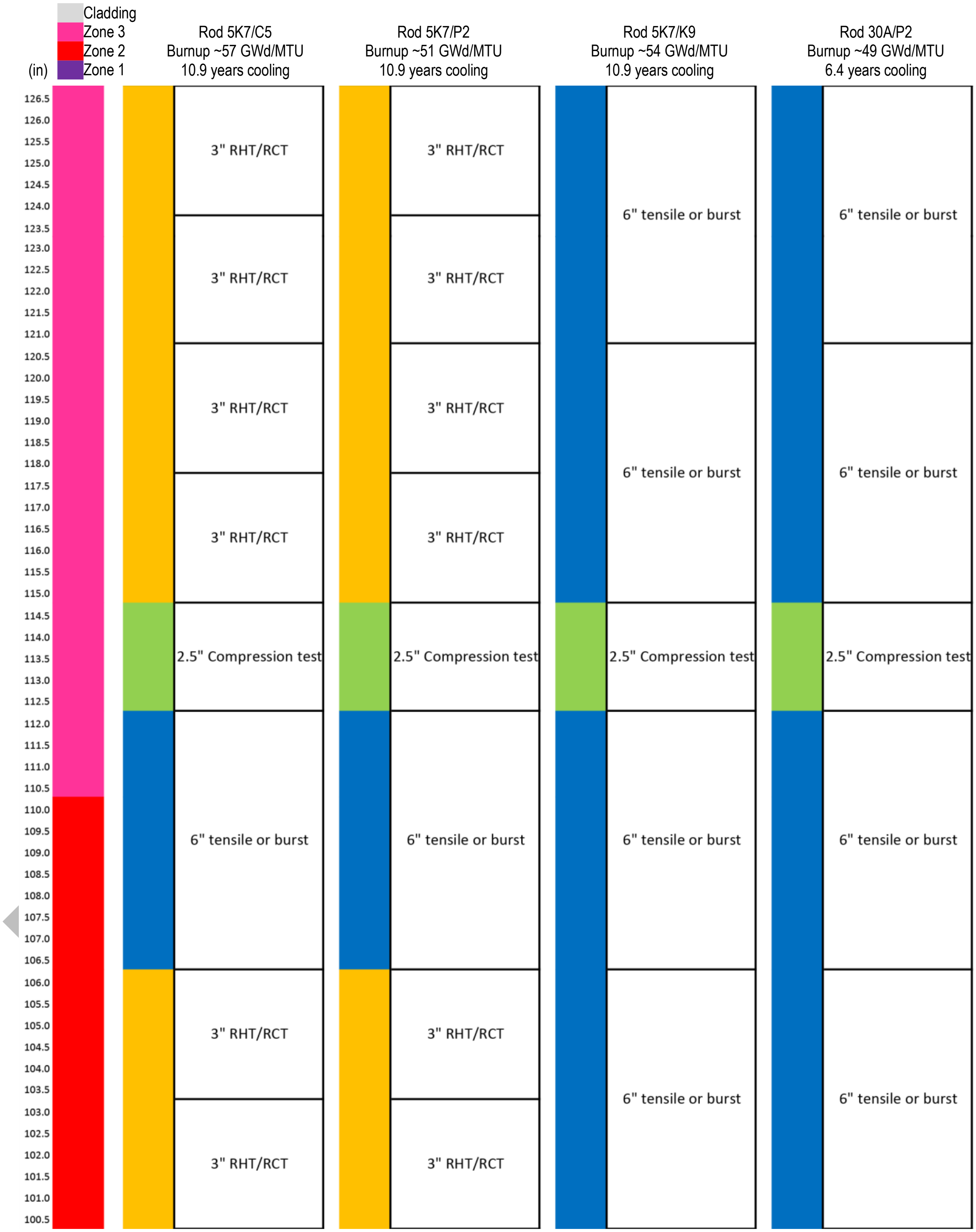
A-1. M5® Sectioning Diagram

Fuel column: 144″; cladding: 152.16″.




Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 5K7/C5
Burnup ~57 GWd/MTU
10.9 years cooling
Rod 5K7/P2
Burnup ~51 GWd/MTU
10.9 years cooling
Rod 5K7/K9
Burnup ~54 GWd/MTU
10.9 years cooling
Rod 30A/P2
Burnup ~49 GWd/MTU
6.4 years cooling
126.5
126.0
125.5
125.0
124.5
124.0
123.5
123.0
122.5
122.0
121.5
121.0
120.5
120.0
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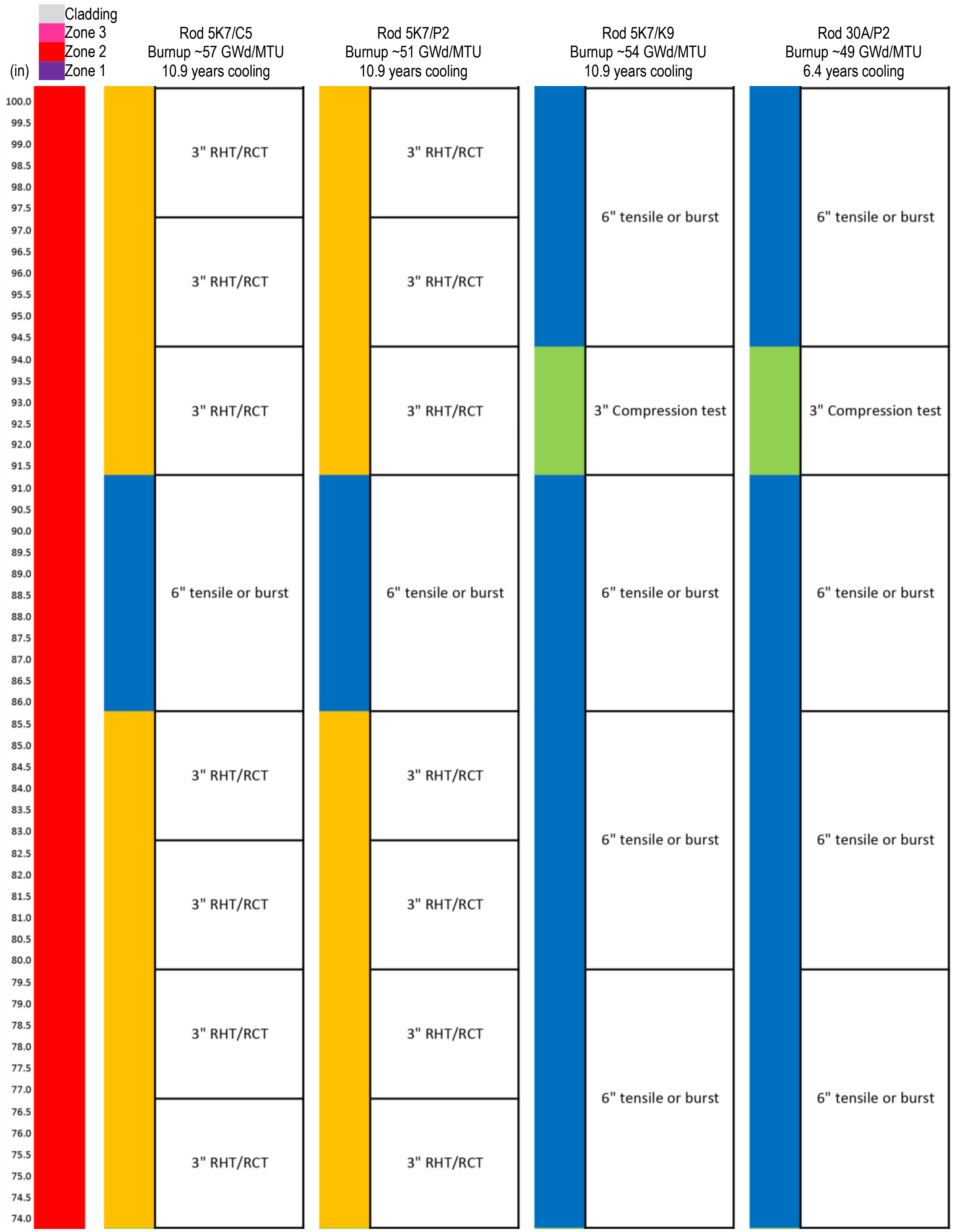
105.5
105.0
104.5
104.0
103.5
103.0
102.5
102.0
101.5
101.0
100.5
3" RHT/RCT
2.5" Compression test
6" tensile or burst



Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 5K7/C5
Burnup ~57 GWd/MTU
10.9 years cooling
Rod 5K7/P2
Burnup ~51 GWd/MTU
10.9 years cooling
Rod 5K7/K9
Burnup ~54 GWd/MTU
10.9 years cooling
Rod 30A/P2
Burnup ~49 GWd/MTU
6.4 years cooling
100.0
99.5
99.0
98.5
98.0
97.5
97.0
96.5
96.0
95.5
95.0
94.5
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93.5
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78.5
78.0
77.5
77.0
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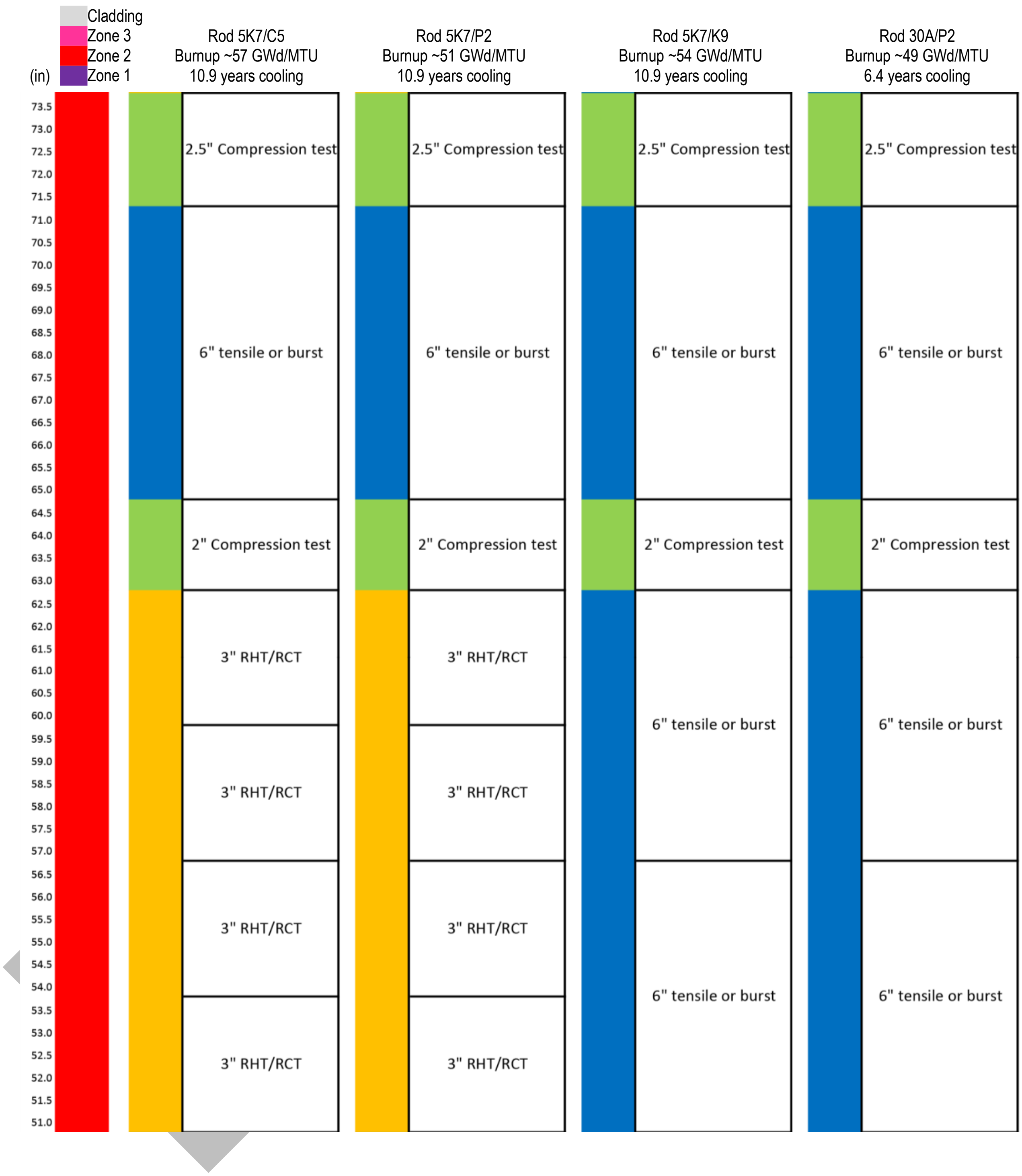
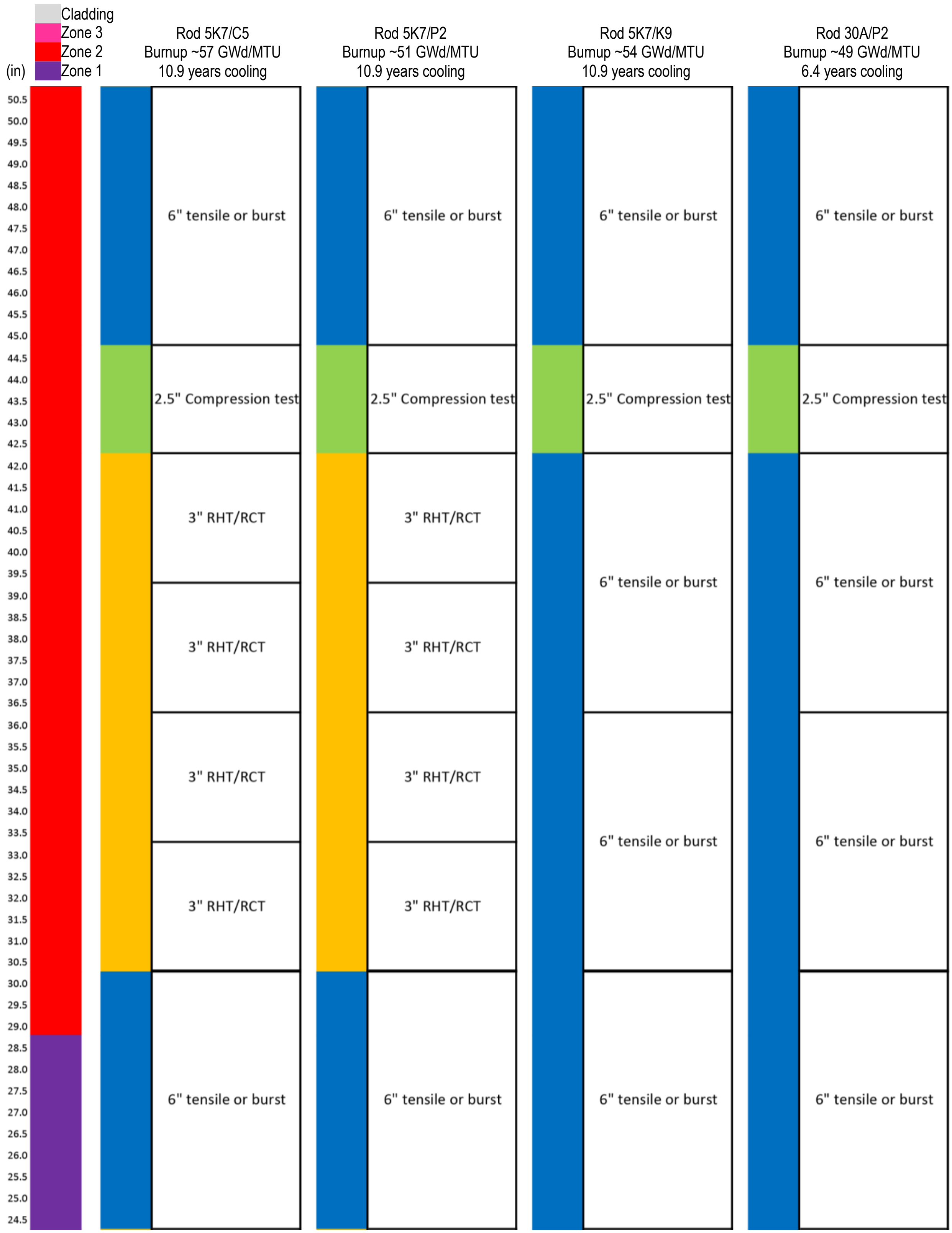
76.0
75.5
75.0
74.5
74.0
3" RHT/RCT
6" tensile or burst
3" Compression test


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 5K7/C5
Burnup ~57 GWd/MTU
10.9 years cooling
Rod 5K7/P2
Burnup ~51 GWd/MTU
10.9 years cooling
Rod 5K7/K9
Burnup ~54 GWd/MTU
10.9 years cooling
Rod 30A/P2
Burnup ~49 GWd/MTU
6.4 years cooling
2.5" Compression test
6" tensile or burst
2" Compression test
3" RHT/RCT
6" tensile or burst


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 5K7/C5
Burnup ~57 GWd/MTU
10.9 years cooling
Rod 5K7/P2
Burnup ~51 GWd/MTU
10.9 years cooling
Rod 5K7/K9
Burnup ~54 GWd/MTU
10.9 years cooling
Rod 30A/P2
Burnup ~49 GWd/MTU
6.4 years cooling
50.5
50.0
49.5
49.0
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
44.5
44.0
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43.0
42.5
42.0
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40.5
40.0
39.5
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37.0
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33.5
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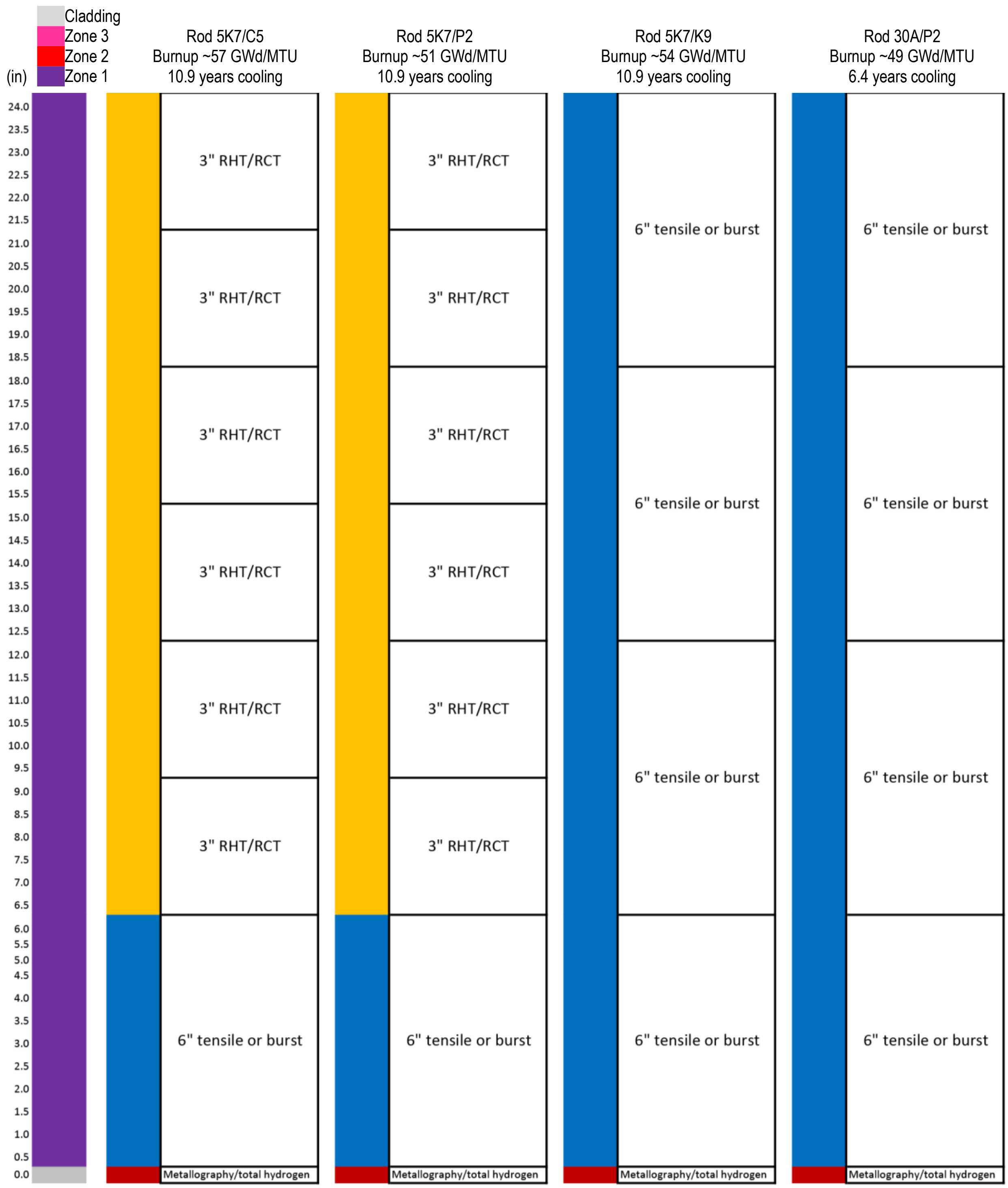
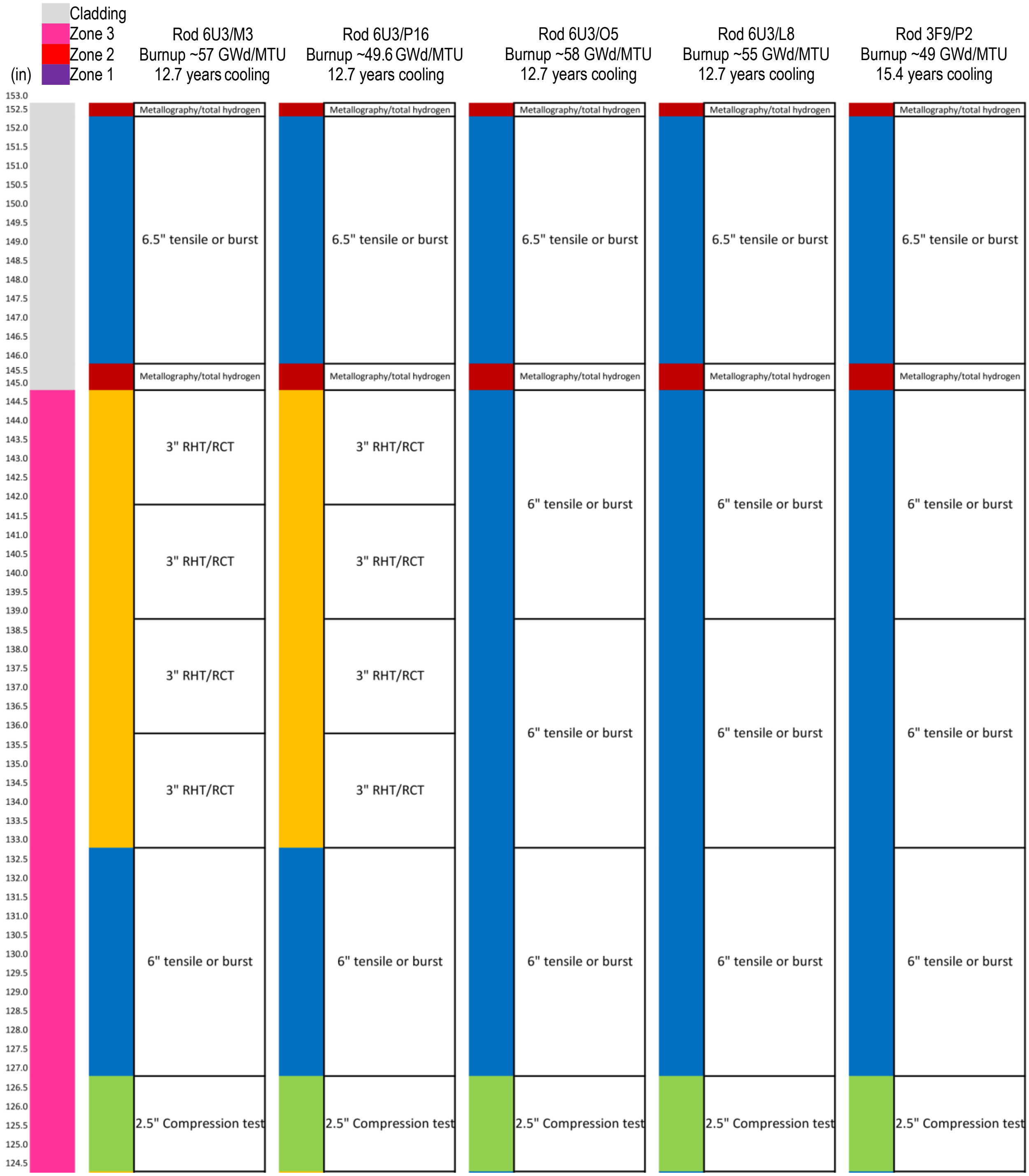
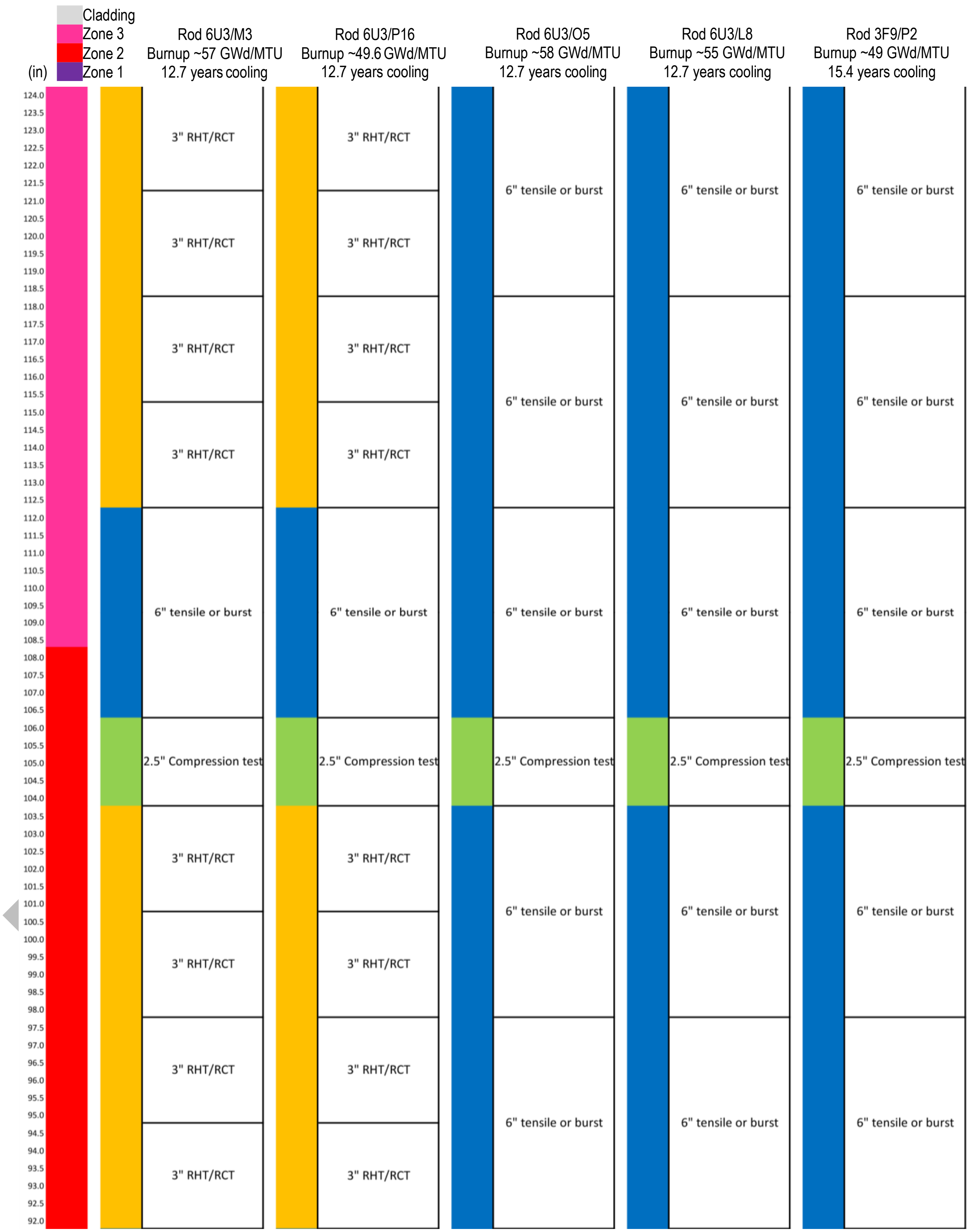
32.5
32.0
31.5
31.0
30.5
30.0
29.5
29.0
28.5
28.0
27.5
27.0
26.5
26.0
25.5
25.0
24.5
6" tensile or burst
2.5" Compression test
3" RHT/RCT

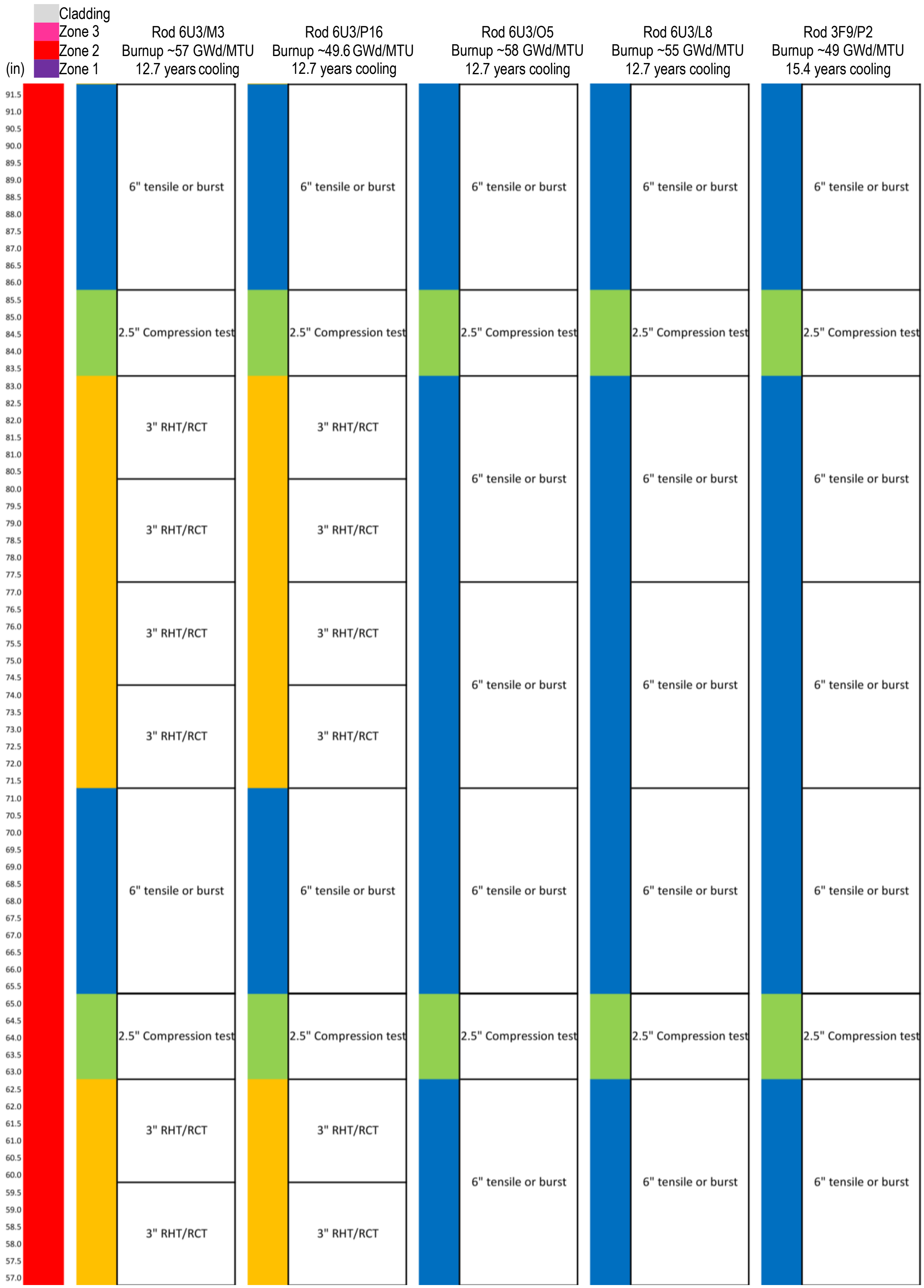

Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 5K7/C5
Burnup ~57 GWd/MTU
10.9 years cooling
Rod 5K7/P2
Burnup ~51 GWd/MTU
10.9 years cooling
Rod 5K7/K9
Burnup ~54 GWd/MTU
10.9 years cooling
Rod 30A/P2
Burnup ~49 GWd/MTU
6.4 years cooling
3" RHT/RCT
6" tensile or burst
Metallography/total hydrogen

A-2. ZIRLO® Sectioning Diagram

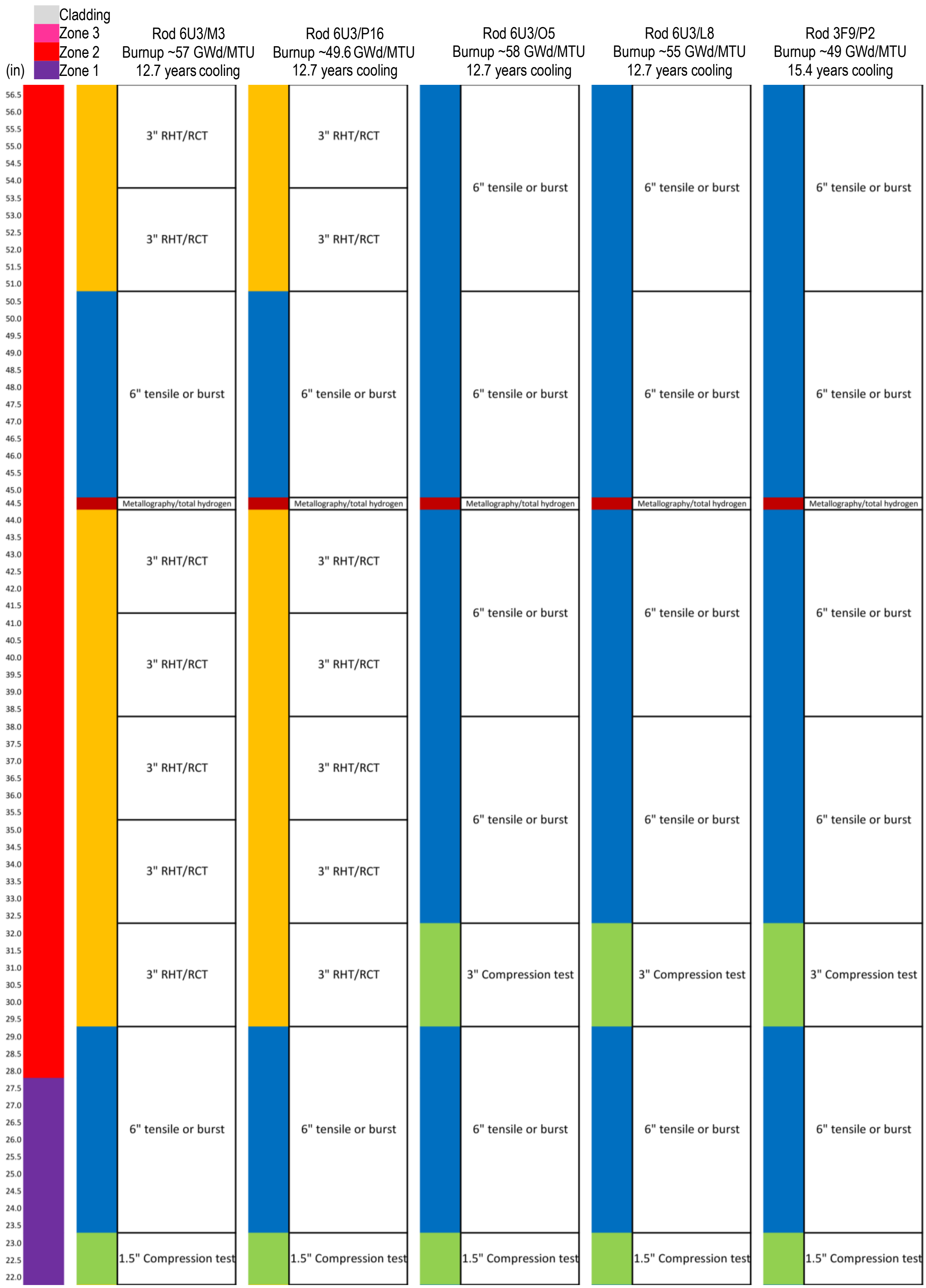
Fuel column: 144″; cladding: 152.8″.

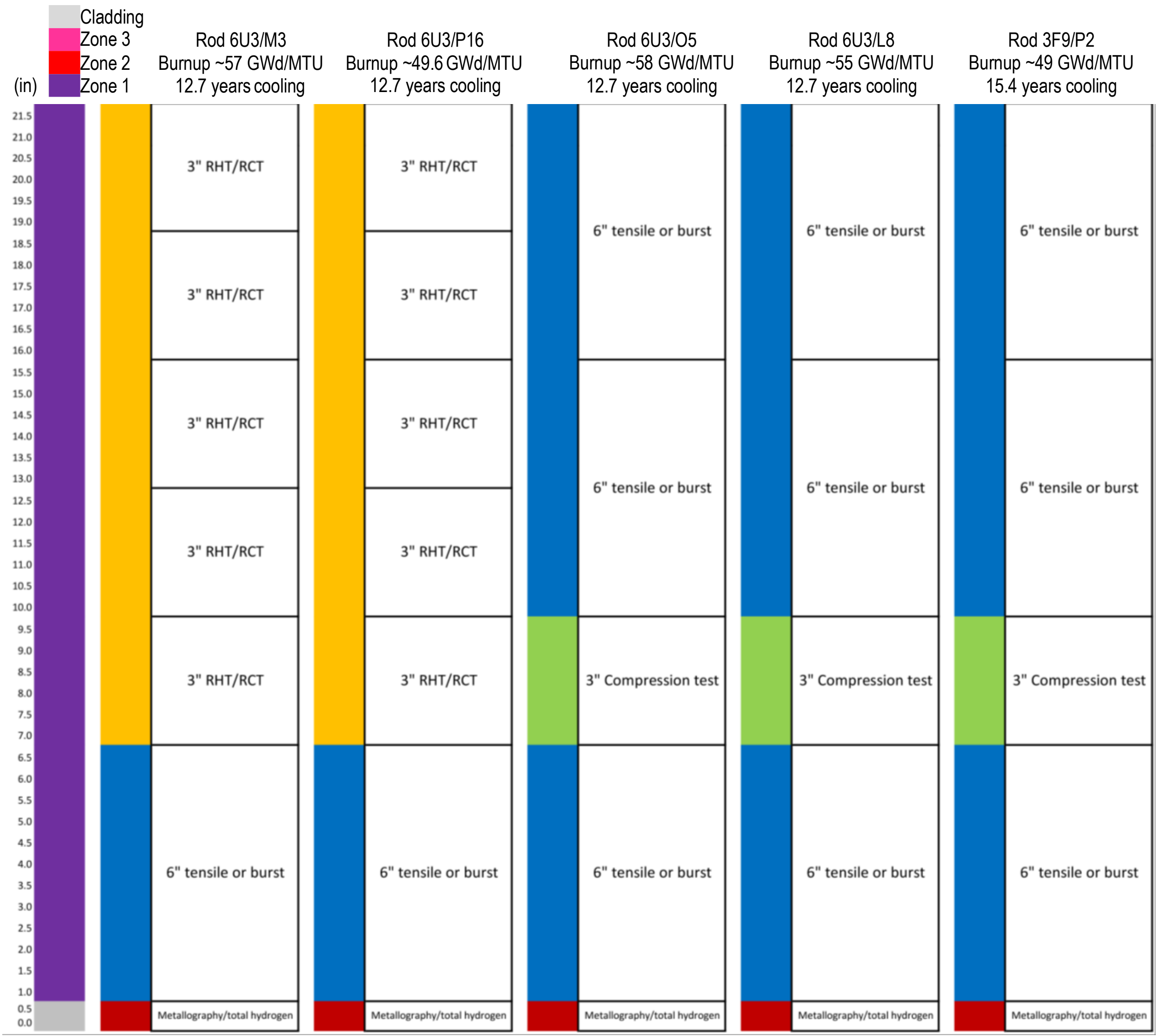



Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 6U3/M3
Burnup ~57 GWd/MTU
12.7 years cooling
Rod 6U3/P16
Burnup ~49.6 GWd/MTU
12.7 years cooling
Rod 6U3/O5
Burnup ~58 GWd/MTU
12.7 years cooling
Rod 6U3/L8
Burnup ~55 GWd/MTU
12.7 years cooling
Rod 3F9/P2
Burnup ~49 GWd/MTU
15.4 years cooling
3" RHT/RCT
6" tensile or burst
2.5" Compression test



Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 6U3/M3
Burnup ~57 GWd/MTU
12.7 years cooling
Rod 6U3/P16
Burnup ~49.6 GWd/MTU
12.7 years cooling
Rod 6U3/O5
Burnup ~58 GWd/MTU
12.7 years cooling
Rod 6U3/L8
Burnup ~55 GWd/MTU
12.7 years cooling
Rod 3F9/P2
Burnup ~49 GWd/MTU
15.4 years cooling
6" tensile or burst
2.5" Compression test
3" RHT/RCT


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 6U3/M3
Burnup ~57 GWd/MTU
12.7 years cooling
Rod 6U3/P16
Burnup ~49.6 GWd/MTU
12.7 years cooling
Rod 6U3/O5
Burnup ~58 GWd/MTU
12.7 years cooling
Rod 6U3/L8
Burnup ~55 GWd/MTU
12.7 years cooling
Rod 3F9/P2
Burnup ~49 GWd/MTU
15.4 years cooling
3" RHT/RCT
6" tensile or burst
Metallography/total hydrogen
3" Compression test
1.5" Compression test



Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod 6U3/M3
Burnup ~57 GWd/MTU
12.7 years cooling
Rod 6U3/P16
Burnup ~49.6 GWd/MTU
12.7 years cooling
Rod 6U3/O5
Burnup ~58 GWd/MTU
12.7 years cooling
Rod 6U3/L8
Burnup ~55 GWd/MTU
12.7 years cooling
Rod 3F9/P2
Burnup ~49 GWd/MTU
15.4 years cooling
3" RHT/RCT
6" tensile or burst
3" Compression test
Metallography/total hydrogen

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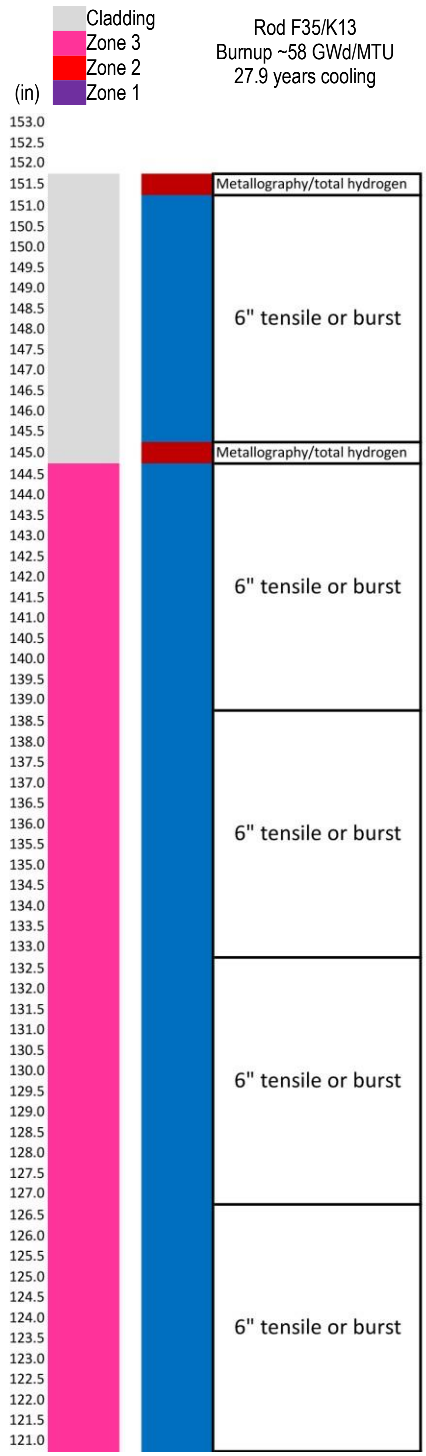
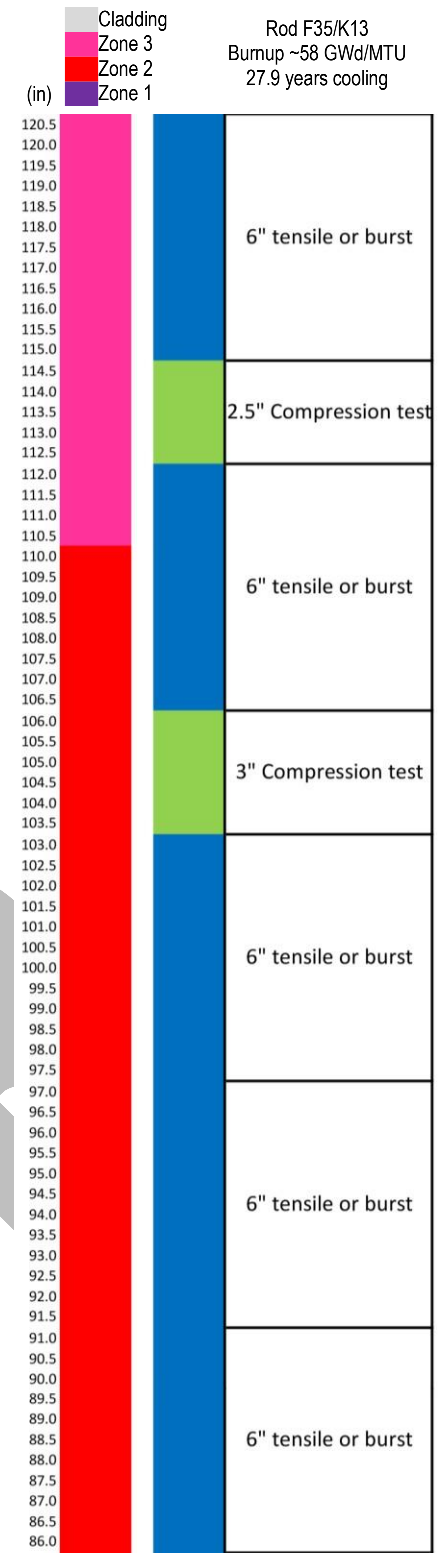
A-3. Zr-4 Sectioning Diagram

Fuel column: 144″; cladding: 151.635″.




Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod F35/K13
Burnup ~58 GWd/MTU
27.9 years cooling
120.5
120.0
119.5
119.0
118.5
118.0
117.5
117.0
116.5
116.0
115.5
115.0
114.5
114.0
113.5
113.0
112.5
112.0
111.5
111.0
110.5
110.0
109.5
109.0
108.5
108.0
107.5
107.0
106.5
106.0
105.5
105.0
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103.5
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98.5
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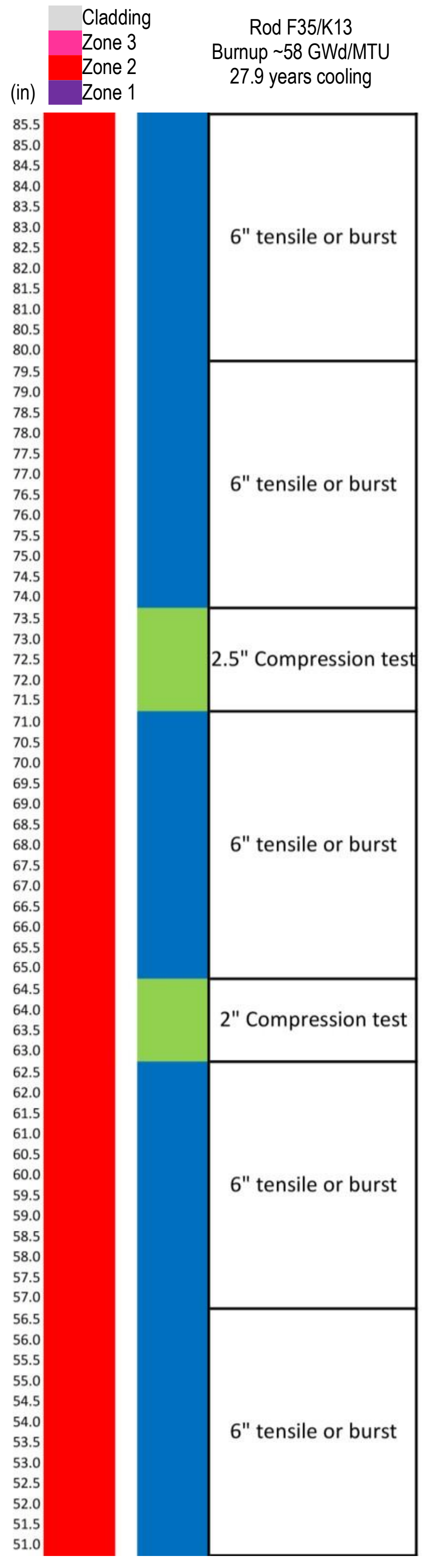
93.5
93.0
92.5
92.0
91.5
91.0
90.5
90.0
89.5
89.0
88.5
88.0
87.5
87.0
86.5
86.0
6" tensile or burst
2.5" Compression test
6" tensile or burst
3" Compression test
6" tensile or burst
6" tensile or burst
6" tensile or burst


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod F35/K13
Burnup ~58 GWd/MTU
27.9 years cooling
85.5
85.0
84.5
84.0
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
78.5
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76.5
76.0
75.5
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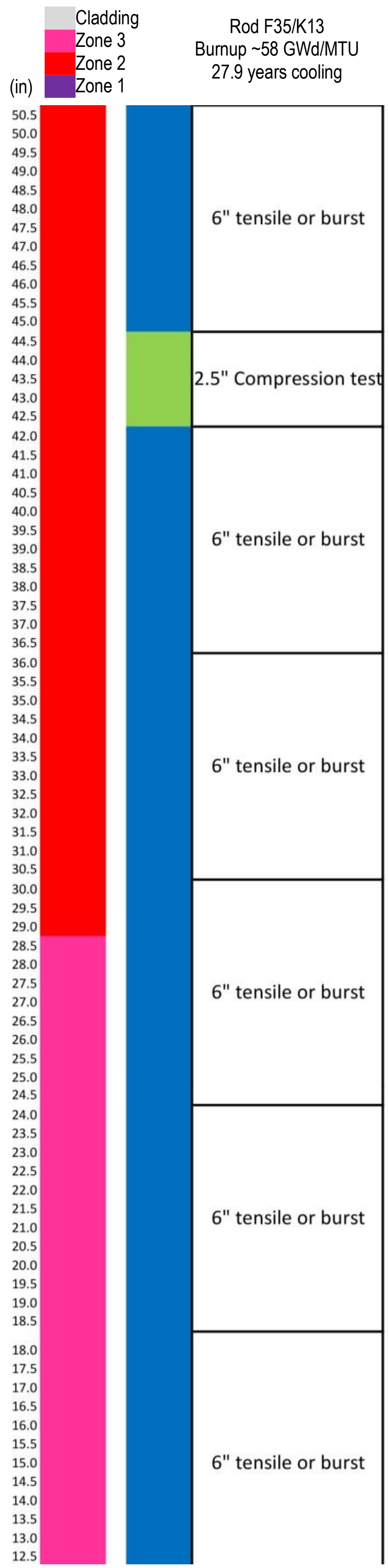
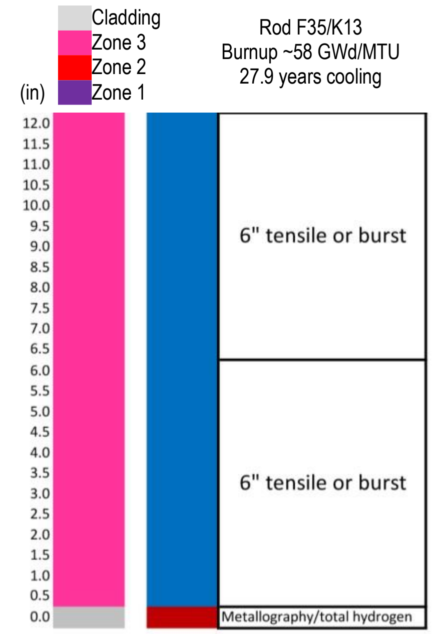
58.5
58.0
57.5
57.0
56.5
56.0
55.5
55.0
54.5
54.0
53.5
53.0
52.5
52.0
51.5
51.0
6" tensile or burst
6" tensile or burst
2.5" Compression test
6" tensile or burst
2" Compression test
6" tensile or burst
6" tensile or burst


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod F35/K13
Burnup ~58 GWd/MTU
27.9 years cooling
6" tensile or burst
2.5" Compression test
6" tensile or burst
6" tensile or burst
6" tensile or burst
6" tensile or burst
6" tensile or burst
50.5
12.5


Cladding
Zone 3
Zone 2
Zone 1
(in)
Rod F35/K13
Burnup ~58 GWd/MTU
27.9 years cooling
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6" tensile or burst
6" tensile or burst
Metallography/total hydrogen

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